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DEVELOPMENT OF A BIOWASTE RESISTOJET PROPULSION SYSTEM

Final Report

Prepared under Contract No. NAS1-10961
by McDonnell Douglas Astronautics Company
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

This final report on Development of a Biowaste Resistojet Propulsion System Propellant Management and Control Subsystem is submitted by McDonnell Douglas Astronautics Company (MDAC) to the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, as required by Contract Number NAS1-10961. The work was conducted under the technical direction of Mr. Earl VanLandingham and Mr. Cecil Nichols of the Space Technology Division of Langley Research Center.

This report contains the preliminary design of the resistojet system, the supporting system analysis, the design modifications for the ground test model, and the development program producing the model.

Requests for further information concerning this report will be welcomed by:

- R. V. Greco
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ACKNOWLEDGMENTS

Technical support in the area of advance technology components was provided to the program by the Marquardt Company (vaporizer) and Metal Bellows Company (compressors).

Acknowledgment is also extended to the following MDAC personnel who contributed significantly to the results of this study. These individuals and their areas of contribution are:

J. L. Fowler, Stabilization and Control

W. G. Nelson, Environmental Control and Life Support

D. L. Endicott, Compressor Development

W. R. Downs, Reliability and Maintainability

H. C. Wilkinson, System Fabrication and Testing

M. L. Beutler, Jr., Electronics Design

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UNITS OF MEASUREMENTS

Units, abbreviations, and prefixes used in this report correspond to the International System of Units (SI) as prescribed by the Eleventh General Conference on Weights and Measures and presented in NASA SP-7012. The basic units for length, mass, and time are meter, kilogram, and second, respectively. Throughout this report, the English equivalent (foot, pound, and second) are presented for convenience.

The SI units, abbreviations, and prefixes most frequenctly used in this report are summarized below:

Basic Units

Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	degree Kelvin	°K

Supplementary Units

Plane angle	radian	rad

Derived Units

Area	square meter	m^2	
Volume	cubic meter	m^3	
Frequency	hertz	Hz	(s^{-1})
Density	kilogram per cubic meter	kg/m^3	
Velocity	meter per second	m/s	
Angular velocity	radian per second	rad/s	
Acceleration	meter per second squared	m/s^2	
Angular acceleration	radian per second squared	rad/s^2	

Force	newton	N	(kg-m/s^2)
Pressure	newton per sq meter	N/m^2	
Kinematic viscosity	sq meter per second	m^2/s	
Dynamic viscosity	newton-second per sq meter	N-s/m^2	
Work, energy, quantity of heat	joule	J	(N-m)
Power	watt	W	(J/s)
Electric charge	coulomb	C	(A-s)
Voltage, potential difference: electromotive force	volt	V	(W/A)
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	(V/A)
Electric capacitance	farad	F	(A-s/V)
Magnetic flux	weber	Wb	(V-s)
Inductance	henry	H	(V-s/A)
Magnetic flux density-	tesla	T	(Wb/m^2)
Magnetic field strength	ampere per meter	A/m	
Magnetomotive force	ampere	A	

Prefixes

Factor by which unit is multiplied	Prefix	Symbol
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ

Section 1
INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The advent of long-term manned spaceflights for sophisticated Earth-oriented and inertial experiments imposes increasingly stringent requirements on the stabilization and attitude control (S/AC) subsystem and the propulsion and reaction control system (RCS). MDAC studies of the Manned Orbital Research Laboratory (MORL) and the NASA Space Station have identified control-moment gyros (CMGs) as the best system for the primary attitude control of manned spacecraft. Use of resistojet systems has been identified as being the best way to perform the spacecraft orbit-keeping function, as well as providing simultaneous CMG desaturation. These studies furthermore showed that resistojets, operating on the residual gases from the environmental control and life support (EC/LS) system, would save a considerable amount of propellant resupply weight and would provide effective disposal of otherwise useless biowastes. The scope and diversity of these studies, however, did not provide the in-depth evaluation required for development of such a system, and MDAC received a 10-month NASA Resistojet Systems Studies contract (NAS1-10127) to define the design requirements and operational characteristics, and to identify the technology necessary to develop a biowaste resistojet system.

Two key technology items identified in this systems study were thrustor development and a ground-test model assembly of a flight propellant management and control subsystem. To perform these technology development tasks, NASA/LRC awarded two contracts (NAS1-10934 to Artcor Company; and NAS1-9474 to Marquardt Company) for thrustor development, and a contract to MDAC (NAS1-10961) for Development of a Biowaste Resistojet Propulsion System's Propellant Management and Control Subsystems. This document is the final report for Contract NAS1-10961.

1.1.1 Biowaste Resistojet Propulsion System Background

The use of resistojets to perform orbit-keeping and CMG desaturation functions on manned space stations was first identified in the MORL study conducted for NASA by MDAC. The use of residual EC/LS gases was considered, but the development status of both EC/LS and propulsion technology precluded selection of such a system; therefore, resistojet propulsion systems utilizing resupplied propellants such as ammonia (NH_3) and hydrogen (H_2) were recommended. A subsequent resistojet systems study further defined the system design and Marquardt developed and life-tested (8,000 hr) a resistojet **thrustor.**

Later, the NASA Space Station program, as defined by MDAC, also selected control-moment gyros (CMGs) for primary control but with a biowaste resistojet system for simultaneous orbit-keeping and CMG desaturation. Selection of biowaste resistojet system was the result of complex system and integrated system tradeoffs, using program and vehicle requirements; program guidelines and constraints; and the conventional cost, weight, power, volume, and crew-time criteria. The vehicle requirements affecting biowaste resistojet system selection were that the vehicle was to:

1. Provide near-zero gravity. Manufacturing and bioscience experiments require long periods of vehicle operation at 10^{-5} g or less.
2. Minimize external contamination. Earth-resource and solar astronomy experiments are extremely sensitive to particulate and molecular species, and also to the deposition of propulsive exhaust products on optical surfaces.
3. Provide for compatibility and adaptability to future missions and experiments. The nominal Space Station altitude and inclination are 456 km (246 nmi) and 55 deg. Capability is required, however, over the altitude range of 371 to 556 km (200 to 300 nmi) and at inclinations ranging from 28 to 55 deg. The station's future growth into the Space Base and operation in synchronous orbit are also desired, with minimum modification. It was further desired that the Space Station be compatible with the requirements of experiments that are not yet defined.

As a result of these vehicle requirements, the following system requirements were established:

A. CMG sizing requires that desaturation be performed frequently (about once per orbit).

B. Orbit-keeping with the use of high thrust can be deferred to occasions when it will not interfere with near-zero-gravity experiments, or low thrust can be used nearly continuously.

C. Provisions must be made for disposal of excess biowastes, which may be either periodically or continuously expelled overboard, in a directed manner, or collected for return to Earth.

D. The selected propulsion systems must have the capability for growth to expanded missions.

System and system-integration tradeoffs were performed on the basis of these requirements. The conclusions were:

A. A biowaste resistojet system can efficiently and effectively provide both CMG desaturation and orbit-keeping, using waste atmosphere regeneration gases. Biowaste availability on both the Space Station and Space Base is such that the baseline system has excess capability and could therefore accommodate the required growth without a change in the system design.

B. CMG desaturation by magnetic torquers or a low-thrust chemical system, orbit-keeping with a high-thrust chemical system, and environment-control and life-support (EC/LS) system capability to collect, store, and expel biowaste gases meet the vehicle and system requirements. Growth of the chemical propulsion system for future missions would require additional impulse capability.

C. Collection and storage of EC/LS system biowastes for return to Earth imposes significant design penalties.

D EC/LS system biowaste collection, storage, and expulsion in a directed manner result in equipment similar to (but simpler than) the biowaste resistojet system.

These conclusions resulted in the selection of the biowaste resistojet system as being the most responsive to vehicle gravity-level and contamination

requirements, providing reduced resupply weight, and disposing of otherwise useless biowastes. The required in-depth evaluation required for system development, however, was not within the scope of the Space Station program, and an additional, in-depth system study was conducted to provide a preliminary design for a biowaste resistojet system and identify the technology items requiring additional development.

The resulting system design uses waste CO_2 and CH_4 from the atmosphere regeneration assembly and excess water as propellants for the resistojet thrustors, which have a thrust level of 0.111 N(0.025 lb) and are used in a high-duty-cycle (25 to 80 percent) mode. The storage, feed, and control assemblies consist of compression pumps, heat exchangers, accumulators, supplementary propellant tankage, thrustors, and the necessary valves and switches for subsystem control and checkout, permitting the biowaste gases to be used, stored, or supplemented with water at all times.

This arrangement is required to ensure EC/LS and resistojet operational independence and provide the necessary thrustor duty cycle and use. Thus, at any given time, propellant use can be determined by impulse requirements and operational constraints, and is not dictated by EC/LS production rate. The combination of varying solar activity and number of attached modules results in a 1,335 to 11,150 N-s/day (300 to 2,500 lb-s/day) impulse range at 456 km (246 nmi). Since the biowaste gases will produce 3,120 to 15,000 N-s/day (1,200 to 3,370 lb-s/day), maximum flexibility is clearly desirable. The capability for this range of impulse is obtained by properly selecting the resistojet operating power level. (Sections 2 and 3 furnish details of the flight design and the modifications to obtain a ground test model.)

In addition to the system design, a system development program was also formulated. Its major objectives were to:

A. Develop flight-weight prototype components and assemblies (emphasizing components requiring advance technology)
B. Demonstrate performance and determine characteristics of prototype components in a ground test system model
C. Perform an integrated EC/LS-resistojet system test program.

The development program plan was based on evaluation of current status, launch date expectations, and design requirements. As a result, the following SRT items were identified:

A. Resistojet heater-element materials
B. Resistojet operation with biowaste fluids
C. Water vaporizer
D. Compressors
E. System design and operation.

NASA determined that the best means of achieving these objectives was through inclusion of the water vaporizer and compressors in the system development effort, but by awarding separate contracts for thrustor development.

The thrustor development program was initiated by contracts awarded to Marquardt to develop a thrustor based on their NH_3/H_2 resistojet (developed under the MORL Study) and to Artcor to develop a thrustor based on new technology (ceramic heating element). However, funding problems and NASA consolidation activities forced cancellation after the heater material studies. Results of these efforts are described in References 1 and 2.

1. 1. 2 Resistojet Propellant Management and Control Subsystem

The objective of the NASA-MDAC contract (NAS1-10961) to develop the ground test system was to provide the equipment (excluding thrustors) required to demonstrate the feasibility of a resistojet propulsion system for Space Station attitude control application, using representative simulated crew-biowaste propellants and state-of-the-art resistojet thrustors in the ground simulation test. The specific overall objective of this demonstration program was to provide a biowaste resistojet prototype propellant management and control system sufficiently similar to the flight article to permit concept feasibility and system demonstration testing of interface compatibility, operational characteristics, and system flexibility. The development effort was not intended to be a full-scale development program, nor did it necessitate the use of flight-developed components. It was designed, however, to prove the concept of useful, efficient utilization of EC/LS waste gases and excess H_2O,

and to incorporate components sufficiently similar to flight type to provide the confidence necessary for future flight component and system development.

The scope of this effort included: (1) refinement of preliminary designs and design requirements for a propellant collection and control assembly, power control assembly, and logic assembly; (2) survey, design, fabrication, and delivery of ground simulation prototype and near-prototype equipment which met the design requirements defined in the first task; (3) preparation of equipment operating and maintenance documents for equipment to be used in the ground test program at NASA; and (4) documentation of all phases of the effort, including necessary reporting of reliability and quality assurance actions.

To implement this scope of activities, the contract was organized into the following four major task areas:

Task 1 - Preliminary Design and System Analysis

This task formulates a flight prototype preliminary design, including sequencing electronics, of a resistojet system propellant management and control system and determines the revisions necessary to be consistent with the constraints of a ground-based feasibility demonstration test. This system is based on the flight system preliminary design formulated under NAS1-10127 (Reference 3), supplemented by additional system operation/control and reliability maintainability analysis. System control logic will be formulated for use in setting system duty cycles. System requirements specifications will be generated.

Task 2 - Prototype System Functional Requirements Definition, Design Specifications and Components Survey

The principal function of this task is to convert the ground-modified flight design of Task 1 into the test model to be built in Task 3. A program development plan, combined with the ground-modified design of Task 1, will be used to prepare a breadboard system design including sequencing electronics. This will be the test system design and, to ensure its relevancy, an assessment of its capability will be included. Component selections will be made according to criteria formulated based on the design requirements of Task 1.

Task 3 - System Fabrication, Assembly and Acceptance Test

This effort includes procurement, design, development, fabrication, and acceptance tests of the system and its component parts. Available flight prototype components, as identified in Task 2, will be procured and acceptance tested. A system, consisting of available and modified available components, plus sequencing electronics and special test equipment will be assembled, and acceptance tested. Advanced components will be developed, and retrofitted into the above system to provide the final delivered prototype system.

Task 4 - Technical Advisory Support

This task includes the preparation of the system operation and maintenance manuals. These manuals will define the operation, routine maintenance, adjustment, and calibration provisions of the systems. The necessary technical advisory support for Government installation and checkout will also be provided.

1.1.3 Approach

The principal basis of this development program was the previously mentioned Resistojet Systems Study, recently completed by MDAC. This study was the first step in the technology development of a flight qualifiable system, and the demonstration program represents the second step. Other major documents used in conducting this program were the proposal for this contract (Reference 3) and the RI systems study final report (Reference 4). Both documents were used as the basis for all design and analyses performed in Task 1.

1.2 SUMMARY

The results of this development program are summarized as follows:

A. The initial flight design is unchanged

B. System reliability (mission completion) is greater than 0.9999

C. Detail automatic system operating procedures are realistic

D. Ground system conversion is straightforward

E. Considerable test flexibility exists

F. System operational sequencing enhances test capability

G. Advance state-of-the-art compressors and vaporizer were developed.

The basic system design formulated under system study contract NAS1-10127 was reviewed, and was still found to be the best design. New requirements generated by the modular Space Station study, Rockwell International studies (Reference 4), and various test programs only affected operational characteristics (e. g. , duty cycle, flow ratio, etc.).

Analyses conducted on system reliability and operating procedures showed greater than 0. 9999 probability of mission completion and a readily programmable set of operating procedures. The 0. 9999 reliability does not mean no failures—only that sufficient redundancy, maintainability, etc. , exists to assure mission completion. The procedure for automatic operation are lengthy but straightforward and readily adapted to computer usage.

The conversion to a ground test system produced no loss in performance capability, and the control electronics design provides ample flexibility for any anticipated test program. System event timing is readily adjustable by programming patch boards, and control panel switches allow real-time changes during test operations. Three advance technology components (two compressors and a vaporizer) were developed that definitely advance the state of the art. The compressors are welded metal bellows, and the high-pressure compressor is an entirely new method for compressing gases at these pressures and pressure ratios (compress from 30 psia to 300 psia). The low-pressure compressor and water vaporizer extended existing models.

1. 2. 1 Final Report Scope

This report documents all results of this contract, and is organized as follows:

Section 2. Flight System Design and Analysis - Updates the flight design and presents the results of the analyses to establish impulse requirements, system reliability, operating logic, system sizing, and interface requirements.

Section 3. Ground System Design - Describes the necessary changes to convert the flight system to the ground system design. It includes the design of the electronics for control of the ground system operation.

Section 4. System Development - Describes all aspects of system development from component evaluation to acceptance test results. It forms the largest and most significant section of the report, and is, after all, the primary product of the contract.

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Section 2
FLIGHT SYSTEM DESIGN AND ANALYSIS

One of the first study tasks was to review the system design (Figure 2-1) formulated in the Resistojet System Studies (References 3 and 4) and consider possible modifications from the following additional sources:

A. Modular Space Station impact
B. Alternate EC/LS concepts
C. EC/LS 90-day simulator test results
D. Variable-thrust capability
E. Compressor bypass capability.

MDAC results show that the previously generated preliminary design is still the recommended flight design, but that compressor bypass capability should be included for ground test designs. The system as formulated is compatible with all likely EC/LS interfaces, the 90-day test did not result in any changes in design requirements, and the system already includes sufficient thrust-level flexibility.

Two additional analyses of system reliability and system operation were performed to assure that the flight design concept was valid.

2.1 SYSTEM DESCRIPTION

The design model of the MDAC Space Station resistojet system utilizes bio-waste gases (CO_2 and CH_4) produced by the EC/LS system as propellants, with water as a supplemental propellant, if required. The system minimizes resupply requirements, furnishes a useful method of biowaste disposal, minimizes contamination, and permits near-zero acceleration.

The resistojets have a thrust level of 0.111 N(0.025 lb) and are operated in a high-duty-cycle mode (25 to 80 percent) for Space Station orbit-keeping and

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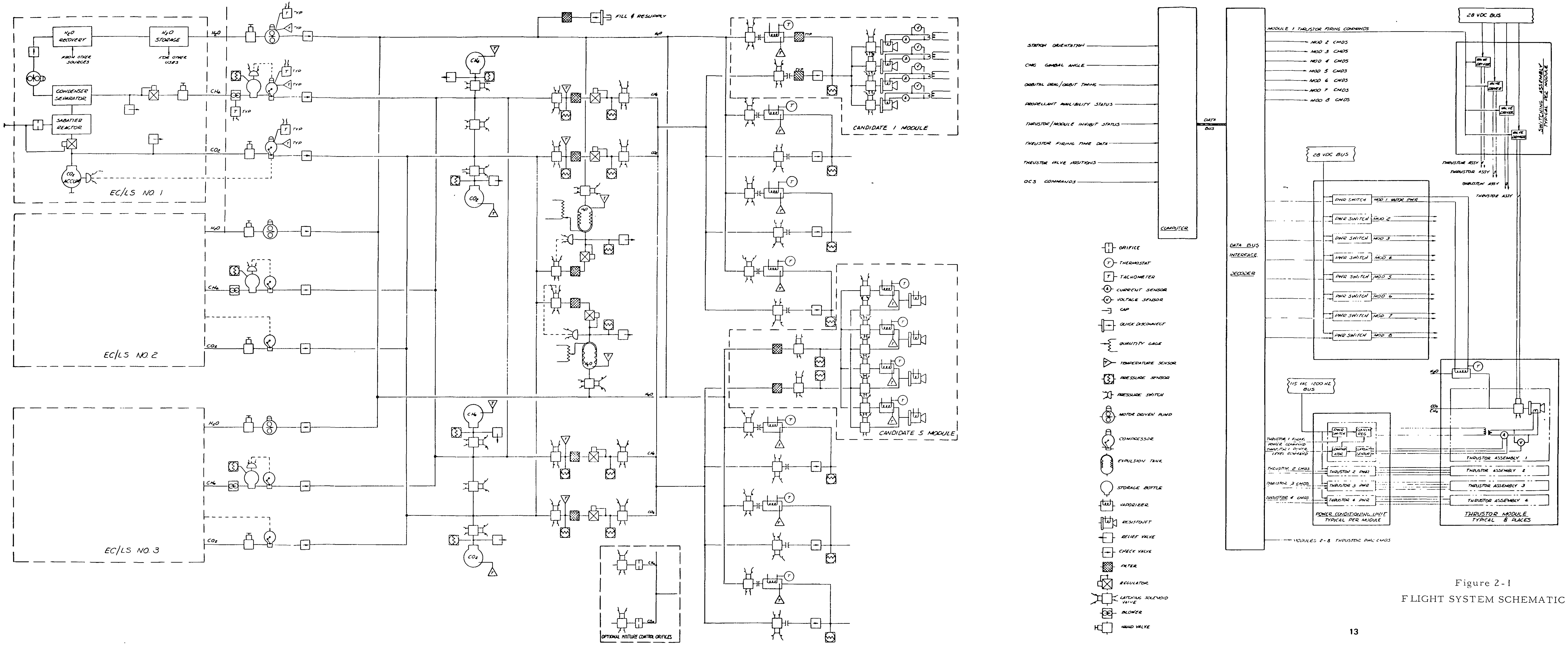

Figure 2-1

FLIGHT SYSTEM SCHEMATIC

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CMG desaturation. The thrustors are mounted in modules, four of which are located at each end of the Space Station. The gas storage tanks are housed in a pressurizable forward compartment. Figure 2-2 shows the general arrangement.

The combination of variations in solar activity and in the number of modules attached to the Space Station results in an impulse range of 1,335 to 11,150 N-s/day (300 to 2,500 lb-s/day) for a 456-km (246-nmi) orbit. Since the biowaste gases will produce 3,120 to 15,000 N-s/day (700 to 3,370 lb-s/day), maximum flexibility is clearly desirable. The capability for this impulse range is obtained by properly selecting the resistojet operating power level. The required power distribution and control electronics to provide this capability are located beneath and adjacent to the thrustor modules.

Thus, the biowaste gases may be used, stored, or supplemented with water at all times. This arrangement assures the operational independence of the EC/LS subsystem and the resistojet system while meeting requirements for propellant usage and thrustor duty cycle. Therefore, at any given time,

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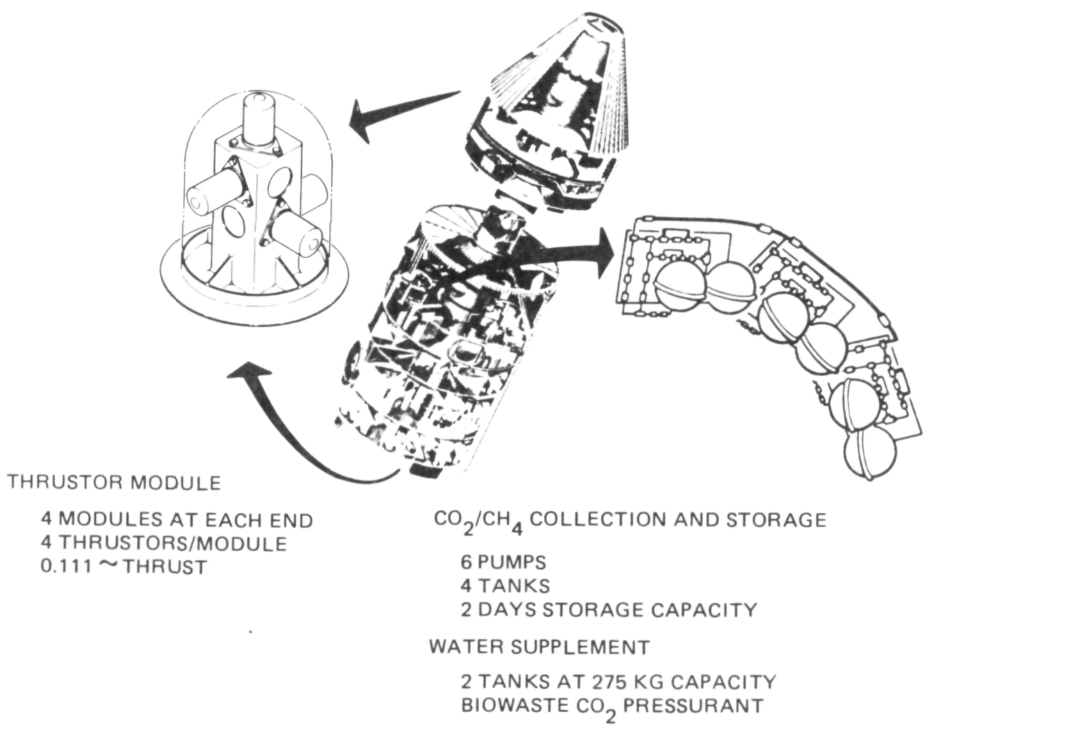

Figure 2-2. Resistojet System Installation

propellant usage can be determined solely by impulse requirements and operational constraints, and need not be dictated by the production range of the EC/LS system.

2.1.1 Assembly Functions

The resistojet system consists of five primary assemblies: (1) collection and storage, (2) water supplement, (3) flow control, (4) thrustor, and (5) power distribution and control. The interrelationships of these assemblies and their interfaces with other subsystems are shown in Figure 2-3 and explained in the following subsections.

2.1.1.1 Collection and Storage Assembly

The collection and storage assembly collects, pumps, and stores the gaseous biowaste outputs from the EC/LS subsystem. Accumulation and storage of the biowaste outputs from the EC/LS subsystem. Accumulation and storage of the gases are necessary to smooth out EC/LS system transients, collect gases when dumping is undesirable, and provide propellant during EC/LS

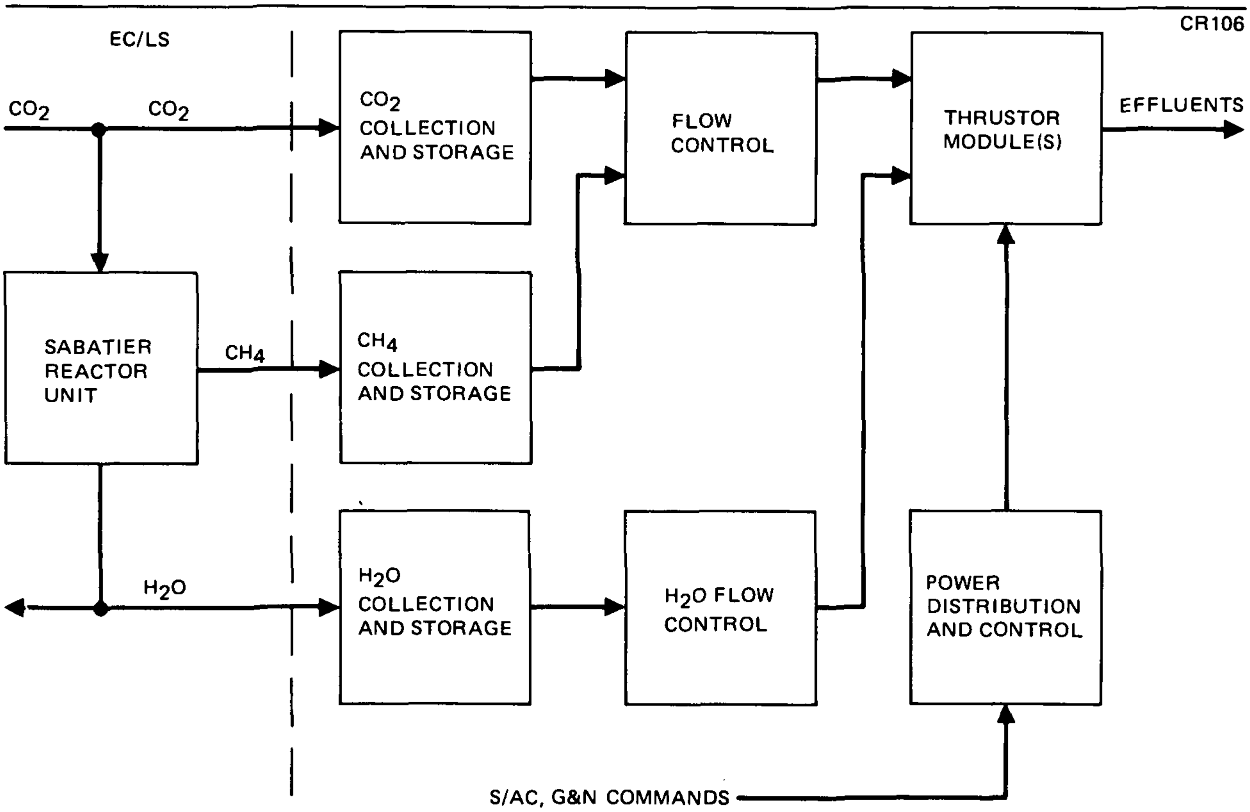

Figure 2-3. Functional Schematic of Resistojet System

system maintenance or when crew size varies from the nominal. Since the Sabatier outlet pressure is only 1.07 x 10^5 N/m^2 (15 psia), however, compression pumping is required for storage in reasonable volumes. The individual gases (CO_2 and CH_4) are compressed to 2.14 x 10^6 N/m^2 and stored in 0.76-in. (2.5-ft)-dia accumulators. Four accumulators are used to provide the reliability of dual tanks for each gas and permit maintainability without interfering with system operation.

Figure 2-4 shows the system and control interface between the EC/LS subsystem and the resistojet collection-and-storage assembly.

2.1.1.2 Water Supplement Assembly

During most of the Space Station's life, the impulse requirements can be easily met by the biowaste gases. When demand exceeds supply, however, heating the CO_2 to 1,550 °K (2,800°R) will produce additional impulse. (The CH_4 cannot be heated above 1,250 °K (2,250°R) or it may dissociate, forming carbon and causing severe deterioration of thrustor performance.) For larger increases in impulse, a supplemental propellant must be used; water

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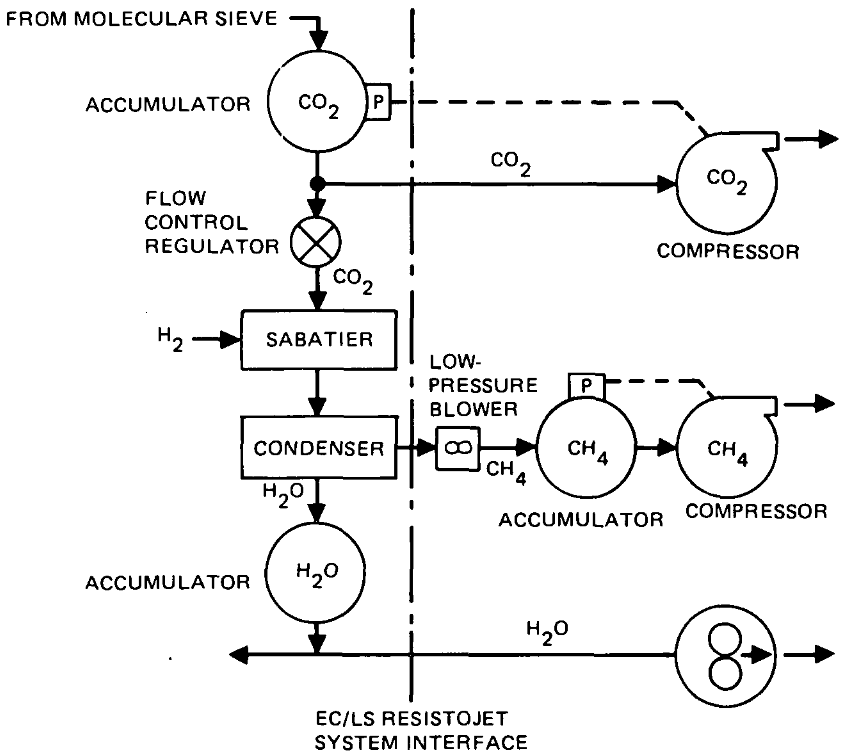


Figure 2-4. Interface Schematic and Compressor Concept

was selected for this purpose because it is easy to resupply and is readily compatible with the thrustors, and because excess EC/LS water will be available.

The water supplement assembly stores the water to provide additional impulse during years of peak solar activity. Two tanks are used to assure maximum reliability, and cross-feed provisions add flexibility. The tanks include positive expulsion devices.

The readily available CO_2 supply makes it the best source of pressurant for water expulsion. The flow demand is negligible, and the weight and complexity of tapping into the biowaste collection assembly are considerably less than the weight and complexity of storing and resupplying a separate pressurant gas.

2. 1. 1. 3 Flow Control Assembly

The flow control assembly regulates and controls propellant flow and is one of the key assemblies in automatic checkout, fault isolation, and maintenance. Its primary function is to furnish a constant supply pressure to the resistojets. All regulators and valves in the assembly are accessible and removable.

2. 1. 1. 4 Thrustor Module Assemblies

The thrustor assembly consists of eight modules (four at each end of the Space Station) with a total of 32 thrustors. It also includes module isolation valves for use during maintenance or repair, and a vaporizer to superheat water before injection into the thrustors.

The number and location of thrustors allow operations in any likely orientation (i. e. , horizontal, perpendicular to orbit plane, inertial, attitude, or trim) with little or no penalty. This arrangement also includes complete redundancy in all operating modes, which permits repair to be scheduled at a convenient time, rather than requiring immediate attention.

2. 1. 1. 5 Power Control Assembly

Thrustor operation is initiated by commands from the power distribution and control assembly, which simultaneously opens thrustor valves, sets power

level, and turns on the heater element. The power level fixes heater current and, therefore, chamber temperature, which determines the flow rate and specific impulse.

Power distribution and control provides two major functions: supplying controlled (variable) power for the thrustor heater and supplying the operating power for propellant storage control and flow control. Variable power for the thrustors is required to match propellant usage to EC/LS-system bio-waste generation, maximize thrustor life, and minimize power consumption. Power level is determined by system operational software, which utilizes guidance, navigation, and control (GNC) gimbal angle and accelerometer data, and resistojet-system operational status data.

Power distribution and control for the thrustor heaters uses power drawn from the 115-vac, 3-phase, 1,200-Hz Space Station bus. Conditioning units and step-down transformers supply the power for the thrustor heaters. Distribution and control elements for propellant storage control and flow control operate from both the 115-vac, 3-phase bus and the 28-vdc bus. The CH_4 and CO_2 compression pumps use the 3-phase ac source.

2.1.2 Impact Assessment

As stated in the introduction of this section, the impact of five specific potential changes on this system were investigated. The results are described in the following subsections.

2.1.2.1 Modular Space Station

The Modular Space Station EC/LS utilizes the same CO_2 removal concept as the 10-m (33-ft)-dia station, and hence will not impact the resistojet-system design concept, although the modular station will only produce CO_2, since the Sabatier has been deleted from the EC/LS system. However, Sabatier retrofit capability is included in the modular station EC/LS design; the prototype resistojet system will provide capability to use EC/LS produced CH_4 as well as CO_2. All other impacts of the Modular Station are operational in nature (duty cycle, increased CO_2, etc.).

2.1.2.2 Alternate EC/LS Concepts

Alternate potential EC/LS systems will not impact the EC/LS-resistojet interface. All currently considered concepts have interfaces that will either produce 2.15-2.9 x $10^5 N/m^2$ (31 to 42 psia), cyclic, intermittent or 1.07 x $10^5 N/m^2$ (15 psia) continuous flow of biowaste gases. Duty cycle and quantities will be affected, but will not impact system design.

2.1.2.3 EC/LS 90-Day Simulator Test

The EC/LS 90-day simulator test results were reviewed, but none of the results impacted on system design. Propellant composition, duty cycles, etc., were different, but not the basic design.

2.1.2.4 Variable Thrust Level

The addition of thrustor metering orifices for additional thrust level variability was studied and rejected. Orifices provide constant flow rate, with variable power producing variable chamber pressure (and hence thrust). This has the advantage of more clearly providing true zero-g, but was rejected for the following reasons:

A. Vehicle capability is already 4:1 (1 to 4 thrustors on at any time), and the additional capability would only be approximately 2.3:1 $\left(\frac{F_{Hot}}{F_{Cold}} = \sqrt{\frac{T_{Hot}}{T_{Cold}}} = \sqrt{\frac{2880}{530}} = 2.3\right)$ where F is thrust and T operating temperature. This is not sufficient to warrant additional complexity.

B. Additional multiple thrustor firing would be required for dumping, since orifices provide constant flow, and hence, the only means of increasing flow is by additional thrustors. The baseline method of using the thrustor throat for flow control will increase flow at lower power settings, such as might be used for dumping.

C. Different propellants will provide different flow rates and thrust level. The difference in gas constants, R, $\left(\sqrt{\frac{R_{CO_2}}{R_{CH_4}}} = \sqrt{\frac{96}{35}} \approx 1.65\right)$ will produce different flow and thrust characteristics for each propellant which impacts the system operational control.

Thus, no flow-control orificing will be added.

2.1.2.5 Compressor Bypass

Provisions to minimize compressor usage by providing a bypass linking the EC/LS accumulator directly to the thrustor feed assembly were evaluated, and are not included for the following reasons:

A. The concept is incompatible with a bipropellant (CO_2 and CH_4) system. The different pressures and continuous CH_4 supply makes such an arrangement impossible. CH_4 at $1.07 \times 10^5 N/m^2$ (15 psia) is too low a supply pressure, and matching thrustor use to a constant, fixed flow is impossible.

B. The half-hour capacity of the CO_2 accumulator does not provide sufficient transient and damping capability to meet the "no EC/LS Impact" constraint.

C. The cyclic pressure, $2.15\text{-}2.9 \times 10^5 N/m^2$ (31 to 42 psia), will provide varying thrust and flow rate, which in turn will place added stresses on the thrustor heater and increase system operational logic complexity and thrustor heater control capability.

D. The high-ratio compressors only have a 5- to 10-percent duty cycle, and reducing it does not warrant increased complexity.

The above disadvantages notwithstanding, bypass capability is recommended for inclusion in the ground test design.

2.2 SYSTEM ANALYSIS

Two major system analyses were conducted to verify concept feasibility: (1) reliability/maintainability, and (2) system operation.

2.2.1 Reliability/Maintainability

The results of a reliability, maintainability, and fault-isolation analysis of the resistojet propulsion system indicate that the design provides a highly reliable (better than 99.99-percent probability of mission success), easily maintainable system. It should be emphasized that this is mission-success reliability, not "no-failure" or design-performance probability. Further, the design concept enhances fault isolation and repair through the use of interchangeable equipment and a high degree of accessibility.

The biowaste resistojet system is designed to tolerate any failure and still provide mission success. It can operate with any of three propellant types: CO_2, CH_4, or H_2O, all supplied by the EC/LS system. (It can also accept H_2O via resupply.) Figure 2-5 and Table 2-1 show the results of the reliability analysis.

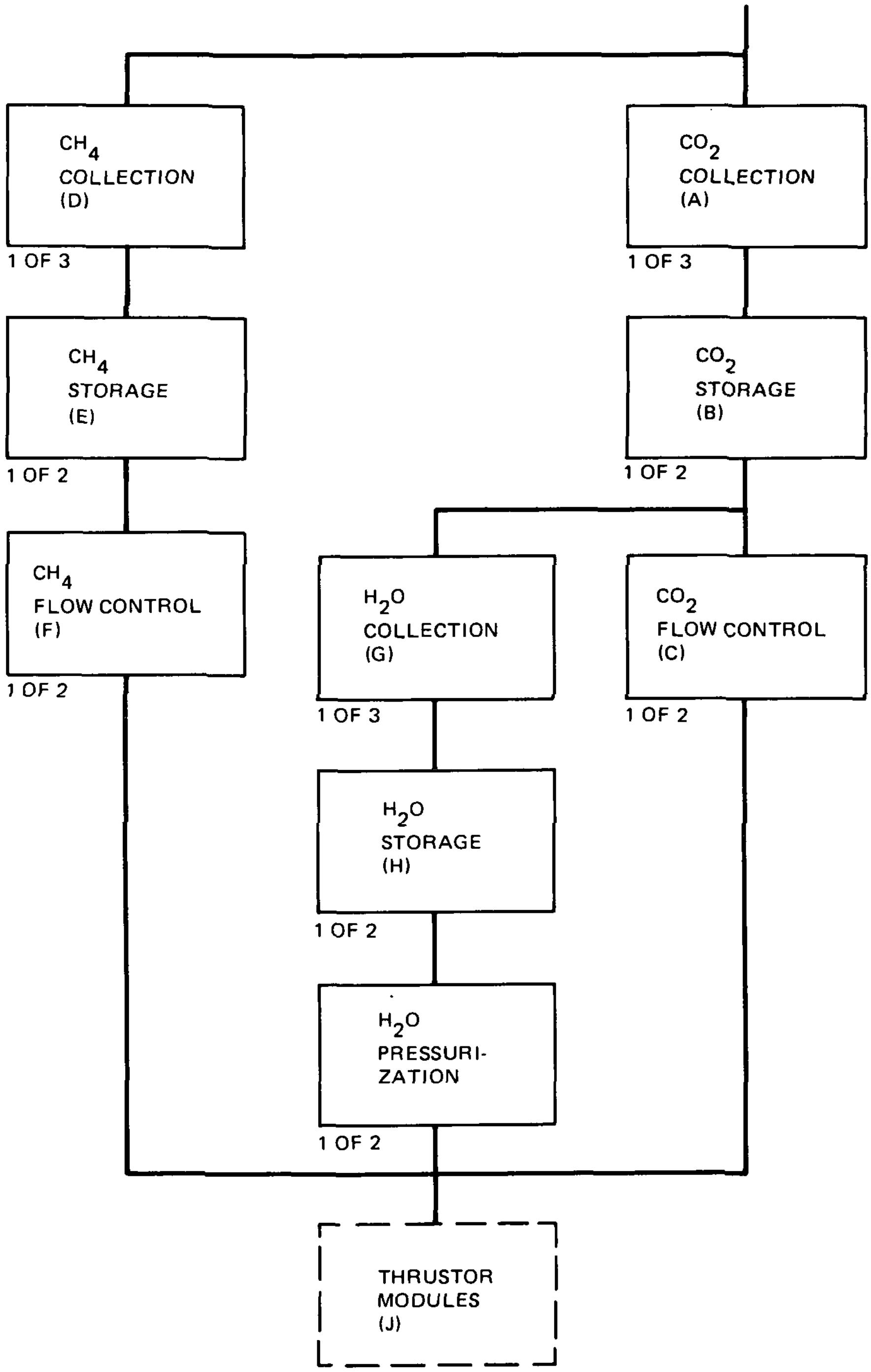
In computing these reliability estimates, it was assumed that every functional element is necessary. As such, temperature sensors and pressure sensors were considered in the evaluation. An on-orbit period of six months was used for numeric computation since on-orbit replacement is intended for failed units. The probability of success was found to be better than 99.99 percent, which is due to the high degree of redundancy and the backup provisions in the design. This does not mean failures are likely or that performance will not be reduced, but that the system probability of performing the required tasks is 99.99 percent.

In addition to the computation of reliability, recommendations for design priorities, spares, quantities and priorities, and accessibility for replacement were included in the analysis.

Table 2-1

RESISTOJET SYSTEM RELIABILITY SUMMARY

Configuration	Probability of Mission Success (percent)
Resistojet system	0.999975
System without H_2O equipment	0.999943
Propellant handling equipment only	0.999994
Propellant handling less H_2O equipment	0.999968
CO_2 propellant handling equipment only	0.994550
CH_4 propellant handling equipment only	0.994101
Power distribution and control equipment only	0.999990



$$R = \left\{ 1 - (1 - R_A R_B [1 - \left\{ 1 - R_C \right\} \left\{ 1 - R_G R_H R_I \right\}] (1 - R_D R_E R_F) \right\} R_J$$

$R = 0.999969$

Figure 2-5. Resistojet System Reliability Model

Maintainability is the feature ensuring that the designed-in reliability is retained during operation. Since failures must be anticipated, spares and access to the failed unit must be provided. The recommendations were derived from the greatest gain in reliability per pound of added weight. A total of about 50 kg (110 lb) is required for onboard spares. The priority of spares provisioning is presented in Table 2-2 (in descending order).

For a satisfactory onboard repair capability, fault isolation must be rapid and definite. The resistojet propulsion system was analyzed for this feature. Any functional component failure can be detected for repair or isolation. These fault isolation provisions are a necessary part of maintenance and every component in this subsystem has at least one fault isolation indicator. Procedures for the optimum benefit from these features have yet to be developed, but the design concept provides the necessary equipment.

Table 2-2

SPARES PRIORITY SUMMARY

Spares Priority	$\Delta R/\Delta W$
First Pressure Sensor	0.4525
First Solenoid Valve	0.1125
Second Pressure Sensor	0.0923
First Motor-Driven Pump	0.0518
Temperature Sensor	0.0425
Thrustor Module	0.0156
Gas Blower	0.0145
Third Pressure Sensor	0.0125
Compressor	0.0123
Second Solenoid Valve	0.0089
Gas Regulator	0.0083
Relief Valve	0.0074
Second Motor-Driven Pump	0.0070
Pressure Switch	0.0055
Second Thrustor Module	0.0027
H_2O Storage Tank	0 0026
Second Gas Blower	0.0010
Gas Storage Bottle	0.0010

2.2.2 System Operation

The biowaste resistojet propulsion system is required to operate automatically, with little or no crew participation except for maintenance/repair, etc. Thus, system control logic is required to acquire S/AC data, calculate impulse requirements, determine propellant utilization and provide the necessary operating commands—typically once per orbit. Furthermore, the interface with the EC/LS system (propellant supply) and the high duty cycle and usage (25 to 80 percent each orbit) makes operational control significantly different and more complex than conventional systems. Detailed operational logic and flow chart diagrams were prepared to ensure adequate system design. The format is such that computer programming can be accomplished using these diagrams and tables.

The overall operational functional flow diagram is shown in Figure 2-6. Stabilization/Attitude Control (S/AC) data (e. g., CMG gimbal angles, and orbit parameters) are determined and impulse requirements calculated. Propulsion system data are used in conjunction with the impulse requirements to select thrustors, calculate their power level, and determine propellant utilization. Operating commands are then provided to system components and thrustors.

The system operational control program can be divided into three major parts:

A. Thrustor Selection - Determine thrustor selection based on orientation, inhibits, and past usage.
B. Impulse Requirements Definition - Determine impulse requirements (e. g., impulse magnitude and direction) and propellant availability.
C. System Operation - Determine propellant utilization, thrustor power level, and thrustor firing times based on impulse requirements and system status.

Figure 2-7 shows the master system program with the above three sections enclosed within the heavy boundaries. Details of how this master program is implemented can be found in the Appendix and further summary in the main body of the report is unwarranted.

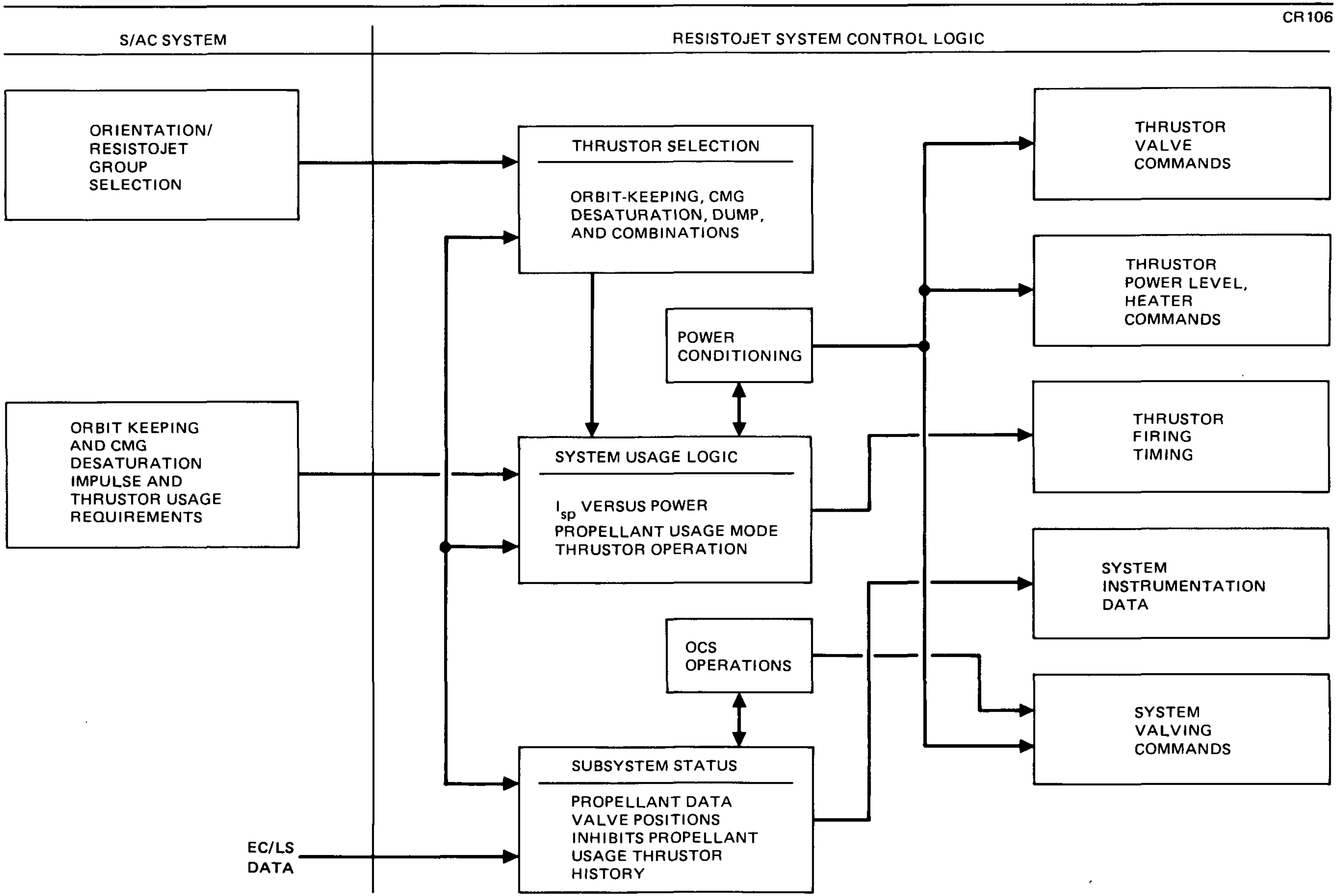


Figure 2-6. Resistojet System Operation

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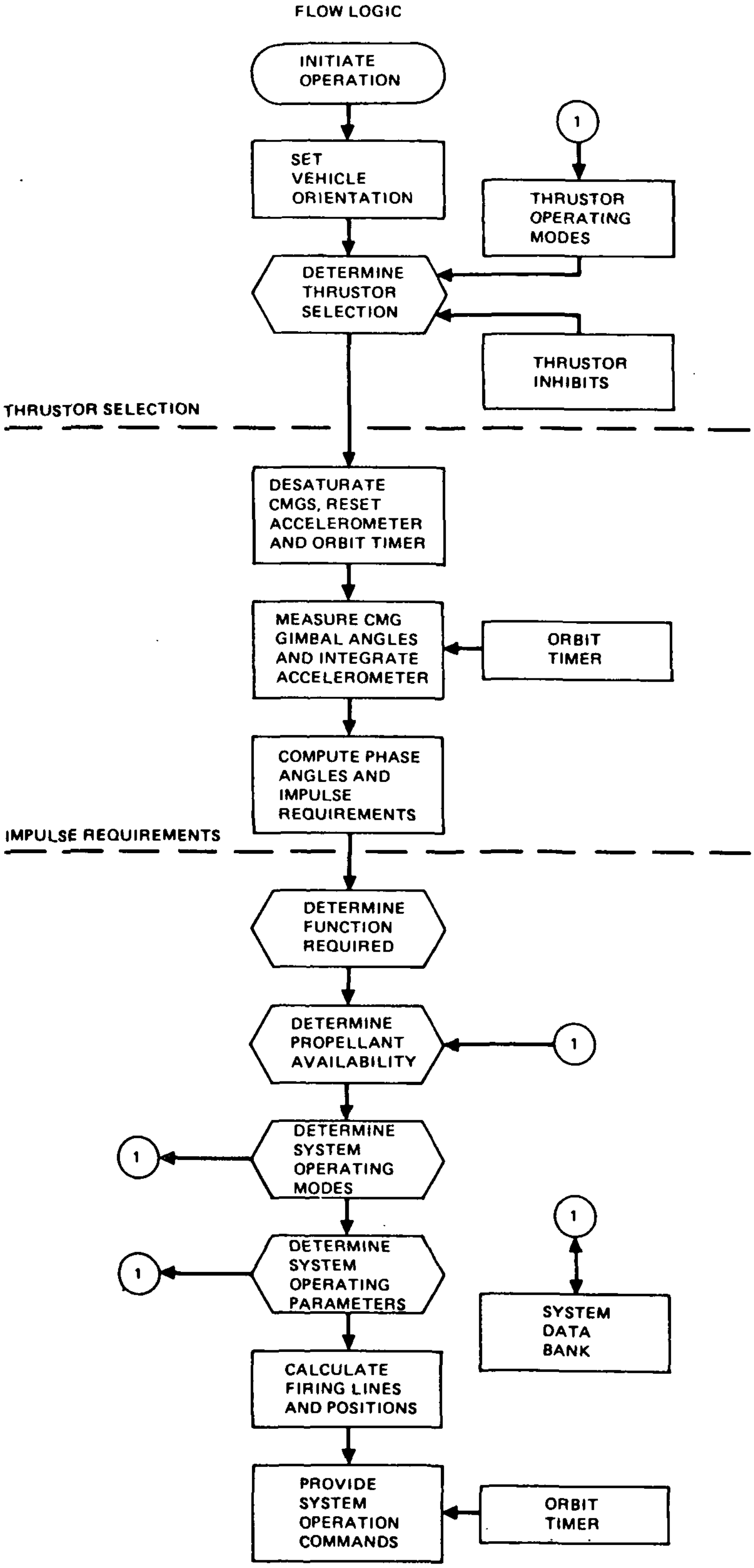

DESCRIPTION

MANUAL CONSOLE SWITCH/KEYBOARD ENTRY

MATCHES THRUSTOR GROUPINGS TO VEHICLE ORIENTATION

DETERMINE THRUSTORS TO BE USED FOR EACH POTENTIAL FUNCTION

INHIBITS FROM SYSTEM STATUS DATA BANK

SET ORBIT TIMER AND NUMBER OF ORBITS TO ZERO AT THE TIME THE CMGS ARE DESATURATED AND THE INTEGRATING ACCELEROMETER OUTPUT IS ZEROED

MEASURES BIAS ANGULAR MOMENTUN AND ΔV IMPULSES AT THE COMPLETION OF ONE ORBIT

CALCULATE IMPULSE REQUIREMENTS

DETERMINE FUNCTIONS TO BE PERFORMED; ORBIT KEEPING, DESATURATION, COMBINATIONS

DETERMINE PROPELLANT AVAILABILITY, INCLUDING QUANTITIES GENERATED (EC/LS), AND STORAGE DUMP REQUIREMENTS

DETERMINE DUMP, SUPPLEMENT, NUMBER OF THRUSTORS, TORQUES, ETC.

DETERMINE SYSTEM OPERATING CHARACTERISTICS WHICH INCLUDE RESISTOJET POWER LEVEL, PROPELLANT QUANTITIES, FLOW RATE, ETC.

CALCULATE ORBIT FIRING TIMES AND POSITIONS

PROVIDE SYSTEM COMMANDS AT APPROPRIATE TIMES

Figure 2-7. Resistojet System Operational Logic

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Section 3
GROUND SYSTEM DESIGN

Since the objective of this contract was to build a ground test system, identification of changes in the flight system was an important task. The significant modifications are as follows:

A. Identify realistic and appropriate ground system interfaces

B. Add a compressor bypass line

C. Identify remote control valving and manual valving (additional or in place of flight remote control)

D. Formulate control console requirements.

To do this the flight test system design was modified to incorporate features providing compatibility with all envisioned/anticipated advancements in both the interfacing environmental control life support (EC/LS) system and bio-waste resistojet thrustor concepts. The resulting ground-test system design contains the following major provisions and features:

A. Collection, storage, and flow-control components for CO_2, CH_4, and H_2O propellants.

B. Resistojet module flow-control elements capable of supplying propellant to four resistojet thrustors operating on various duty cycles and/or thrust levels.

C. Control and sequencing electronic elements necessary to operate the system and the resistojet thrustors.

D. Test support equipment, including power supplies and control console.

E. Provisions for diagnostic instrumentation to the component level.

3.1 INTERFACE IDENTIFICATION

The ground test system is modeled after the flight system design but is assembled to suit the functional objectives of the ground test program and incorporate the control electronics for system operation. The system is

shown in block diagram in Figure 3-1 and consists of two identical collection storage and feed assemblies, a thrustor module assembly, and control electronics assembly.

The thrustor interfaces are defined in the contract to include an entire thrustor module except the thrustors and thrustor inlet valves which are to be provided by the thrustor manufacturers. Thus, only the control signals for the thrustor inlet valve and thrustor heater are provided. Figure 3-2 shows the thrustor module mechanical schematic.

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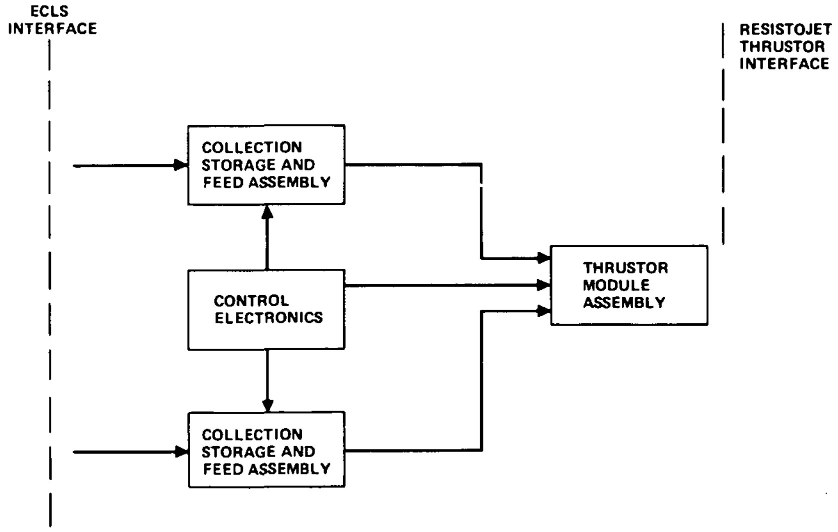

Figure 3-1. Propellant Management and Control Ground Test System

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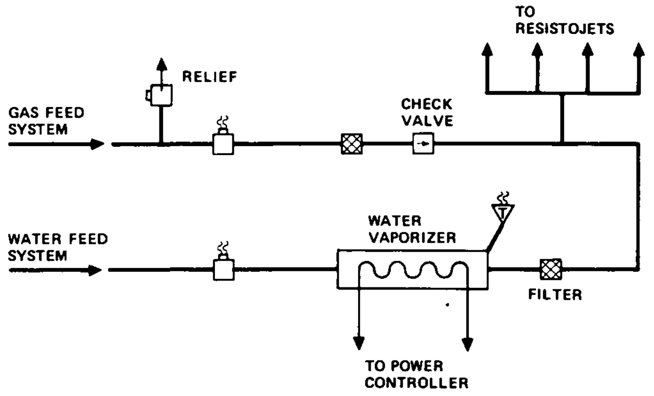

Figure 3-2. Thrustor Module Assembly

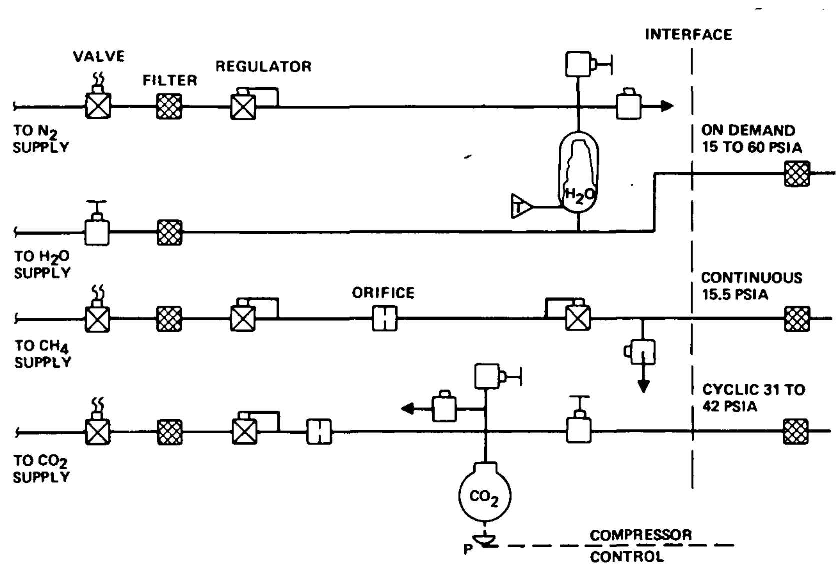

Figure 3-3. EC/LS – Resistojet System Interface

At the inlet end of the system, the interface is defined as the flight vehicle EC/LS resistojet interface except that signals for supply control valves are to be included. Figure 3-3 shows the mechanical interface definition, with MDAC providing the signals to the CO_2 compressor and to the CH_4, CO_2, and H_2O supply valves. Tables 3-1 and 3-2 show the fluid interface requirements and the facility/system power interface, respectively.

3.2 MECHANICAL SYSTEM DESIGN

The heart of the system is the two storage and feed assemblies, shown schematically in Figure 3-4. The CH_4 collection concept is composed of two compressors with intermediate accumulation, and a single compressor for CO_2 collection. The CH_4 from the EC/LS subsystem will be initially compressed at a 2.7:1 compression ratio and stored in a 0.17 m^3 (6-ft^3) reservoir. This is performed continuously and results in a 2.0×10^5 N/m^2 (42-psia) peak reservoir pressure. The second compressor then operates off the reservoir in the same manner (and between the same pressures) as the CO_2

Table 3-1

EC/LS INTERFACE CHARACTERISTICS

Propellant	Pressure	Availability	Closed H_2O-Partially Closed O_2 EC/LS	Closed H_2O-Open O_2 EC/LS
CO_2	31 to 42 psia	Intermittent, controlled from EC/LS accumulator	0.407 kg/man-day (0.9 lb/man-day)	1.0 kg/man-day (2.3 lb/man-day)
CH_4	15.5 ± 0.5 psia	Continuous, no EC/LS accumulator	0.248 kg/man-day (0.55 lb/man-day)	0
H_2O	15 to 60 psia	On demand	TBD	TBD

Table 3-2

FACILITY POWER REQUIREMENTS

Item	Type	Current	Remarks
Power Supplies			
5v	110 vac, 1ϕ, 60~	5 amp, max	25-amp max output.
28v	110 vac, 1ϕ, 60~	14 amp, max	30-amp max output.
Low-Pressure Compressor	208 vac, 3ϕ, 400~	3 amp, max	Compressor activated by relay from control console. 20-amp max start surge. Continuous usage.
High-Pressure Compressor	208 vac, 3ϕ, 400~	5 amp, max	Compressore activated by relay from control console or pressure switch on accumulator. 35-amp max start surge. 5- to 10-percent duty cycles.
Vaporizer	110 vac, 1ϕ, 60~	10 amp, max	Vaporizer activated by relay from control console. Continuous for water usage.
Water Pump	110 vac, 1ϕ, 60~	1 amp, max	Pump activated by relay from control console. Infrequent usage.

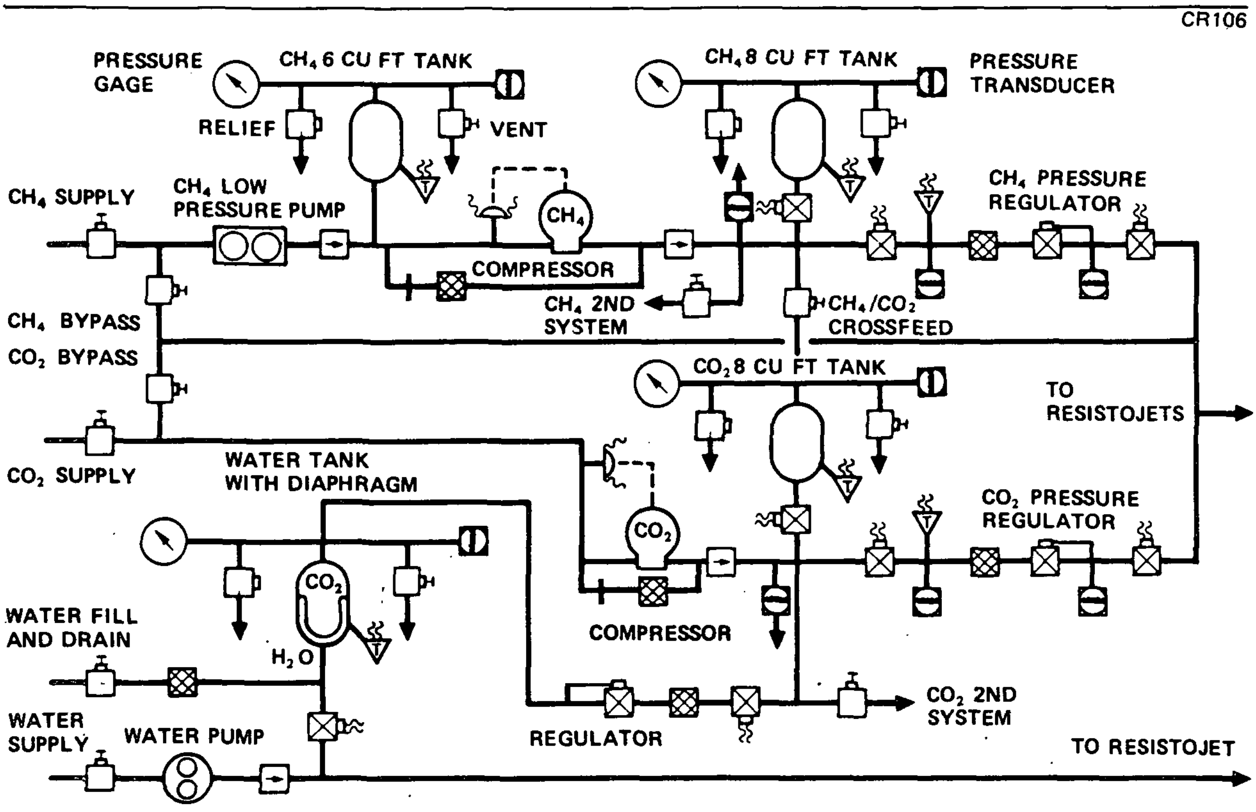

Figure 3-4. Storage and Feed Assembly Schematic

compressor; that is cyclical, initiating at 2.9×10^5 N/m^2 (42 psia), stop at 2.15×10^5 N/m^2 (31 psia). These compressors are identical and will provide the 10:1 compression required for efficient storage. This dual-system arrangement is necessitated by EC/LS differences between the CO_2 and CH_4 interface characteristics.

The requirements of the biowaste accumulators to damp EC/LS gas production and S/AC usage transients, permit prolonged periods of no usage (e.g., experiments, docking maneuvers, etc.), and be unaffected by off-nominal crew sizes (such as during crew rotation or overlap), resulted in approximately 2-day storage capacity of EC/LS output (although normal operation will probably be half capacity). This selection occurred during the Space Station Phase B program when a parametric tradeoff was conducted to determine compressor pumping power and propellant storage (accumulator) volume as a function of the quantity of propellant stored. Selection of 2.14×10^6 N/m^2 (300 psia) accumulator storage pressure was based on the assumption that 2-day biowaste output was to be stored. The actual usable capacities at

2.14×10^6 N/m^2 (300 psia) with blowdown to 0.71×10^6 N/m^2 (100 psia) are 11.2 kg (25 lb) CO_2 and 4.5 kg (10 lb) CH_4, based on four equal-size accumulators (two per propellant).

In addition to the accumulators, this subassembly includes pressure and temperature measurements, a relief assembly, and isolation valve. Pressure and temperature are used for quantity gauging, status monitoring, fault detection, and propellant usage selection. The relief assembly protects against overpressure, and the isolation valve is used for maintenance, fault isolation, and leak detection (pressure decay).

The feed subassembly contains the regulators and valves necessary for flow control, and includes instrumentation and isolation provisions required for monitoring, checkout, etc. Propellant usage is determined by system operating software, which controls valve operations to ensure proper propellant management. Manually set regulators are used to ensure constant-pressure propellant supply to the thrustors, which can be set to any desired pressure.

Constant pressure provides constant thrust, which is necessary for firing-time predictions, total-impulse calculations, and control torque requirements. Two complete subassemblies, with crossfeed provisions are included to ensure maximum flexibility and system operational capability at all times. Although separate propellant usage is the normal operating mode, the system design will permit mixed usage. However, if mixture ratio control is desired, the propellants must be mixed before storage since no flow-rate mixture ratio control is provided.

The remotely controlled valves for this assembly (as well as the other assemblies) are bistable actuator-type (latching) valves. The latching valve requires an activating command to open it and a separate command to close it. Electrical energy is supplied only during the 100-ms duration of the command signals. Usage of this type of valve is based on minimizing power usage and eliminating valve thermal heating problems.

The assembly pressure drops are minimal because of the low flow rates. For most thrustor combinations considered, normal tubing will produce negligible psia drop. Therefore, pressure loss can be virtually ignored except for the vaporizer, thrustor, and possibly thrustor inlet valve. The vaporizer loss will be less than 0.36×10^5 N/m^2 (5 psi). The thrustors and thrustor valves are being supplied by thrustor contractors and the ΔP is unknown (regulators are capable of being set over the range of 2.14 to 3.2×10^5 N/m^2 (30 to 45 psia) to compensate for variable thrustor pressure drop).

In addition to gaseous CO_2 and CH_4, H_2O is also available as a propellant, and a water supplement subassembly is included in the assembly design. This subassembly consists of a pump, tankage, expulsion device, isolation valves, relief assembly, pressurization system, and thermal control provisions. Two cylindrical water tanks, each with 0.05-m^3 (14-gallon) capacity, are included for reliability. The positive expulsion device is of the bladder type. Pressurization is provided by CO_2, tapped from the biowaste CO_2 accumulator and regulated to 4.28×10^5 N/m^2 (60 psia). This readily available CO_2 supply makes it the best source of pressurant for water expulsion. The flow demand is negligible, and the weight and complexity of tapping into the biowaste collection assembly is considerably less than the weight and complexity of storing separate pressurant gas. Refilling the tanks is accomplished by venting (or partial venting) of the ullage. The quantities involved and the low-use requirements make collecting the ullage gases undesirable.

The relief, isolation, and instrumentation provisions are self-explanatory. However, for the ground system, an additional special problem is the potential growth of fungi and bacteria at ambient temperatures in water storage subassemblies which makes water conditioning a potential problem. The flight system solution is added heat (maintain at 345°K), but since the system is to be heated anyway to prevent freezing, the impact is minimal. However, wrapping and heating lines in the ground system is undesirable, and providing heating capability for the tanks may increase effective tank cost and system operating complexity. Line conditioning can be eliminated by draining during periods of prolonged nonusage (regular usage will prevent growth) or using chemical additives, which may not be system and/or thrustor compatible (and

is not the flight procedure). The recommended ground system design consists of unheated tankage and feedlines and an operational procedure to drain and purge every 1 or 2 weeks. This approach provides the least complex, most reliable design without compromising flight system simulation or operational characteristics.

These assemblies will be delivered on two skids, each containing one complete assembly and a flow component panel. Figures 3-5 and 3-6 show the arrangement on each skid, and the component panel, respectively. Components requiring manual control have the handle protruding through the panel for easy access. All components are mounted on the back side.

The compressor bypass lines and numerous hand valves are the result of the studies mentioned in the introduction to this section. The bypass permits direct operation of the resistojets and is primarily useful for thrustor tests when system usage is not required. The inlet supply manual valves permit operation of one skid only. The bypass, crossfeed, and second system valves

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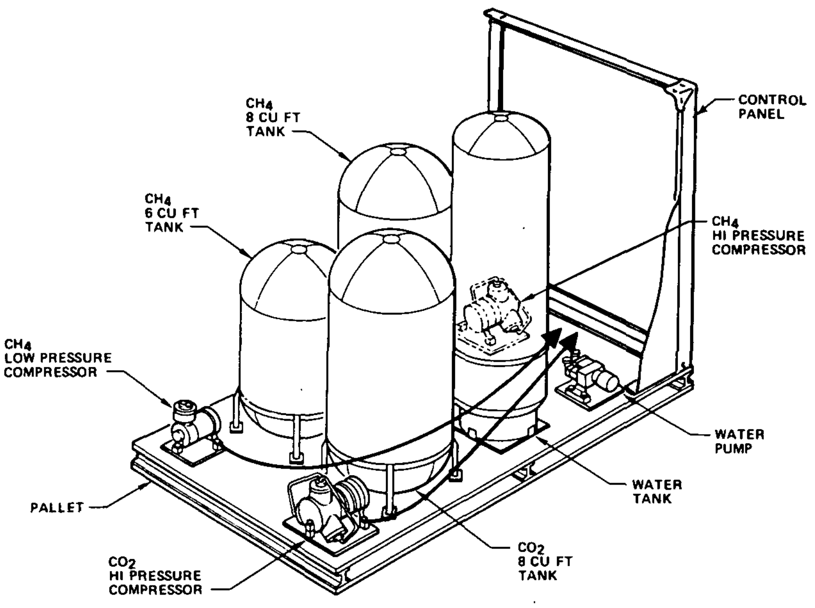

Figure 3-5. Storage and Feed System Arrangement

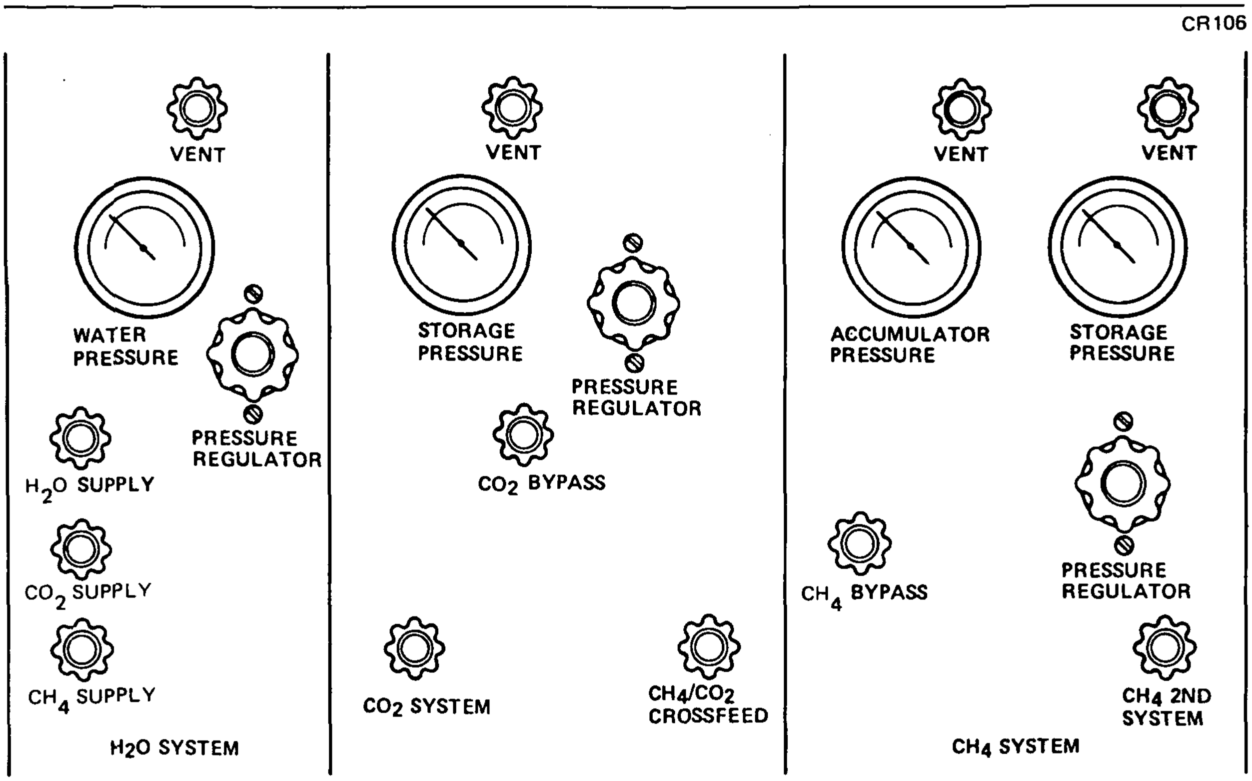

Figure 3-6. Flow Component Panel

are self-explanatory. Hand valves were selected over latching solenoid valves because the infrequent use of these valves made it cost-effective to use hand valves.

3.3 CONTROL CONSOLE DESIGN

As previously stated, the system is to be controlled by a set of sequencers, housed in the control console along with the system valve drivers, relays, timing display, and power supplies. Both semi-automatic and manual operation are provided for. In the semi automatic operation mode, the entire system is sequencer-controlled. The sequencer is organized on a master-slave basis, with the master unit providing overall sequence control and the slave units controlling individual subsequences such as propellant selection or thrustor firing. This approach provides maximum programming flexibility by allowing individual programming of the slave-sequencers and then integration into the master sequencer as required by the test program.

The key requirements of this sequencer setup are:

A. Number of sequencers:

Master - 1

Slaves - 10 (four-thrustor, six-system control)

B. Duration:

Master - 9999.0 sec (2 3/4 hr)

Thrustor Slaves - 9999.0 sec

System Slaves - 999.9 sec (15 min)

C. Timing Interval:

Master and Thrustor - 1.0 sec

System Slaves - 0.1 sec

D. Output Signal Capability:

Master - 20

Thrustor Slaves - 10

System Slaves - 10

Programming of a sequencer is accomplished by simply selecting the time at which each event is desired and patch-wiring the appropriate counter outputs to the control gates. For example, if a particular operation is required at 216.5 sec after sequence start, patches will be made from the two (hundreds), one (tens), six (units), and five (tenths) outputs of the counter to the logic gate controlling that event. Programming is easily changeable by simply repatching. Miniature patch cords are used to minimize area and wiring. In addition, the control console has provisions for manual control inputs for each event to override the automatic sequence if desired, or to allow total manual control of the system from the console. These manual controls also provide the capability to start, stop, and reset the sequencer from the control panel.

The manual controls, plus other system control and status data will be contained in the control console. This control provides control capability for three functions: sequencer operation, system valving, and special component operation (heaters and compressors). The required console functions are provided below:

<u>Sequencers</u> (11) - On/Off indication

- Enable switch

- Shutdown

Valves (25) - Open/Close position
- Open/Close activation

Compressors (8) - Start/Stop
- On/Off indicator

Heaters (5) - On/Off indicator
- On/Off activation

The control layout will group switches and indicators by function to provide maximum visibility of system operation.

Although the thrustors are not supplied by MDAC, the sequencers will provide the activation signal, and system software generated under the study contract will provide the means for preselecting power level. The input power level determines chamber temperature, and hence flow rate and specific impulse. Control of power level is necessary because various propellant compositions require different power inputs for a given chamber temperature.

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Section 4
SYSTEM DEVELOPMENT

Transforming the ground test model design into a real piece of test equipment was the principal task of the contract, and the first step was the formulation and execution of a development plan. This plan, shown in Figure 4-1, resulted in the following major functions:

A. Procurement—Established component specifications, source evaluation/selection procedures, and receiving/inspection requirements.

B. Component Development—Identification and development of advanced technology components (compressors and vaporizer), and acceptance testing of all components.

C. Electronic Design and Development—Detail design of the system control console electronics, fabrication, and assembly of circuit cards and console wiring, and engineering checkout testing of the finished console.

D. Mechanical Subsystem Design and Development—Component panel design, panel and skid fabrication and assembly, storage and feed subsystem assembly, thrustor module assembly, and engineering checkout testing.

E. System Testing—Integration of electrical and mechanical subsystems and final acceptance testing of the completed system.

The overall philosophy in developing this system was to keep formal drawings to the minimum level possible, consistent with adequate visibility. The result was a drawing tree (Table 4-1) listing all drawings, and including a system-test control drawing (TCD) and test procedure drawing (TPD), and a reliability/quality assurance plan (Reference 5) approved by NASA early in the contract. The number of drawings were minimized by assembling the mechanical portions from the schematic and developing wire routing on an as-convenient basis. However, detailed design drawing were required for

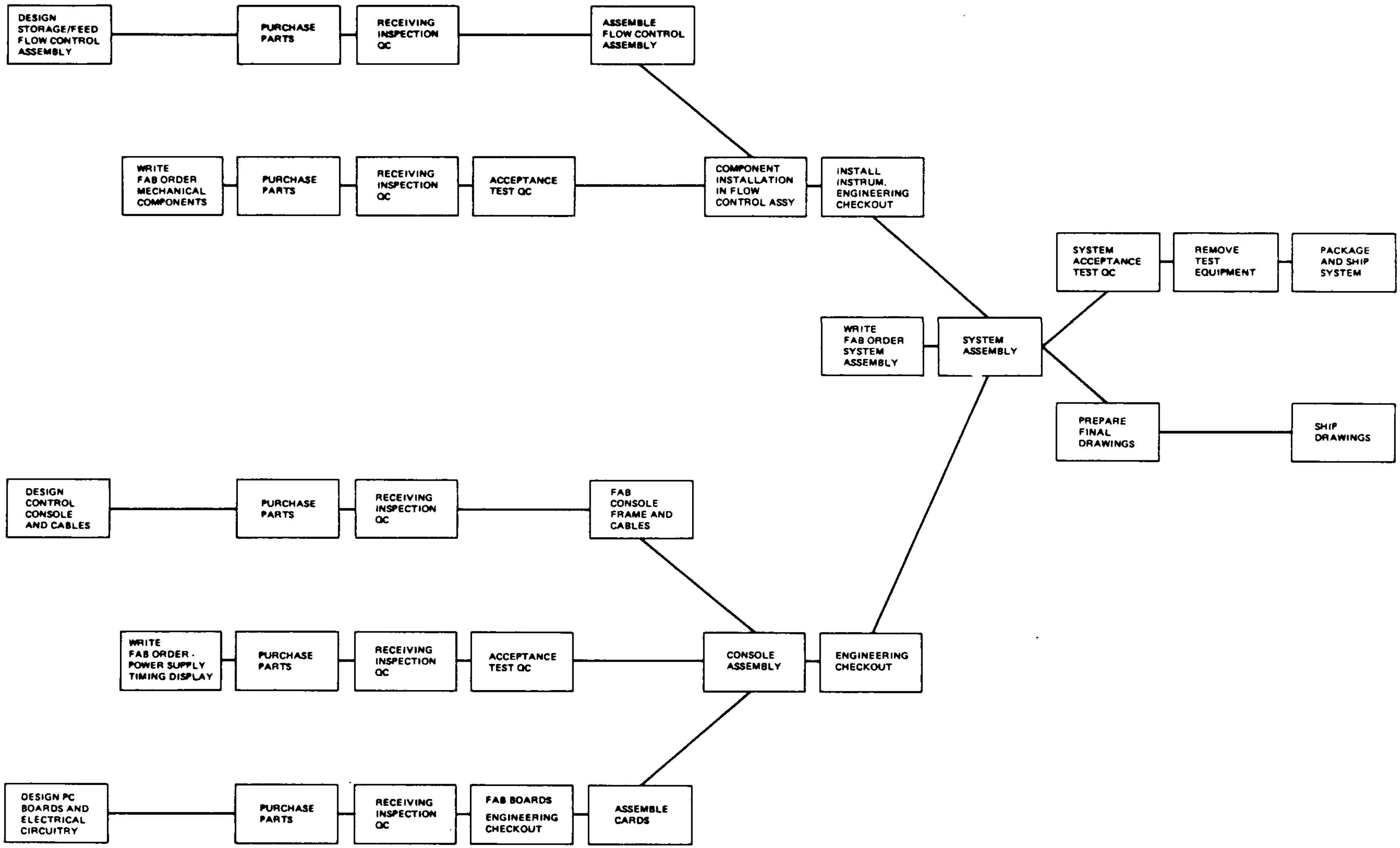

Figure 4-1. System Development Flow Plan

the *electronics* since printed circuit cards require the use of MDAC production facilities.

Table 4-1

DRAWING GENERATION BREAKDOWN
(Resistojet Propulsion System)

Part Number	Nomenclature	Quantity
IT33854	Test Control Drawing	
IT33855	Test Procedure Drawing	
IT33892	Resistojet Propulsion System Drawing	
IT33894	Compressor, High-Pressure, Resistojet	
IT33895	Compressor, Low-Pressure, Resistojet	
IT33896	Vaporizer, Water, Resistojet	
IT33897	Tank, 8 cu ft., Resistojet	
IT33898	Tank, 6 cu ft., Resistojet	
IT33899	Valve, Latching Solenoid, Resistojet	
IT43102	Control Console, Resistojet	
IT43103	Schematic	
IT43104	Logic, Plane Assembly - Four-Row	1
1D33873	Plate, Connector Mounting - Four-Row	1
1D03423	Guide, Circuit Card - Molding	
1D05504	Bar, Guide Mounting, Bottom	4
1D05503	Bar, Guide Mounting, Top	4
1D03321	Plate, End	8
1T42492	Driver, Relay, 600 MA, NPN	10
1T42491	Printed Wiring Board	
1D05571	Printed Wiring Master	
1D05572	Marking Diagram	
1T42494	Circuit Card Assembly, Eight-Relay	8
1T42493	Printed Wiring Board	
1D03333	Printed Wiring Master	
1D03334	Marking Diagram	
1T42835	Circuit Card Assembly, Sequencer	11

Table 4-1

DRAWING GENERATION BREAKDOWN

(Resistojet Propulsion System) (Continued)

Part Number	Nomenclature	Quantity
1T42836	Printed Wiring Board	
1T42838	Circuit Card Assembly, Event Detection	12
1T42839	Printed Wiring Board	
1T42841	Circuit Card Assembly, Clock	1
1T42842	Printed Wiring Board	
1B82353	I/O Circuit Card Assembly	6
1D03670	Printed Wiring Board	
1B88500	Marking Diagram	
1B82359-1	Clamp	
1B82359-501	Clamp	
1B82355-1	Cover	
1T43404	Circuit Card Assembly, Valve Position Memory	4
1T43402	Printed Wiring Board	
1T43470	Wiring Instructions, Wire Wrap Plane	
1T43593	Control Panel, Resistojet	
1T43732	Panel, Resistojet Template Drawing	
1T44418	Cable Assembly, Electrical	
1T44419	Cable Assembly, Electrical	

4.1 PROCUREMENT

Fabrication of the resistojet system required procurement of many different components, most of them purchased unmodified from vendor sources. However, the vaporizer and compressors required additional development effort before they fit the prototype category, which is defined as a flight design concept but not necessarily flight-qualified.

Task 2 of the resistojet-system development contract included conduct of a component availability survey, selection of system components and preparation of a development plan detailing rationale, schedules, etc. The resulting component survey and selection procedure has four major steps: make/buy determination, RFQ preparation, response evaluation, and source selection. Figure 4-2 shows a functional flow block diagram of these steps, plus the other supporting actions necessary for this procedure. These steps are explained below.

4.1.1 Make/Buy Determination

The first step was to revise component availability to determine which components should be bought and which made. As a result of this activity, most components (e.g., valves, filters, etc.) were bought unmodified to vendor part numbers. However, the compressors and vaporizer required additional development to meet prototype requirements, although breadboard models were available without modification.

The electronic equipment (e.g., sequencer, console, valve drivers) were determined to be make items, except for the power supplies, which were bought.

4.1.2 RFQ Preparation

This step prepared a RFQ package to be sent to potential vendors. It included the specifications and work statements as determined by the program, and the pricing criteria, quality assurance, etc., established by company policies. A bidder list was also compiled.

For those components to be bought to a vendor part number, the proposal request required only readily available information (e.g., usage, history, quality assurance, etc.) in addition to cost. However, for the advance components, additional supporting data such as analyses, development schedule, etc., were necessary for confident source selection. All RFQ's were formal in nature, but minimum supplier proposal effort was encouraged.

4.1.3 Evaluation

Proposal evaluation was conducted by an evaluation team which reported to the Source Selection Board. This evaluation team included program personnel,

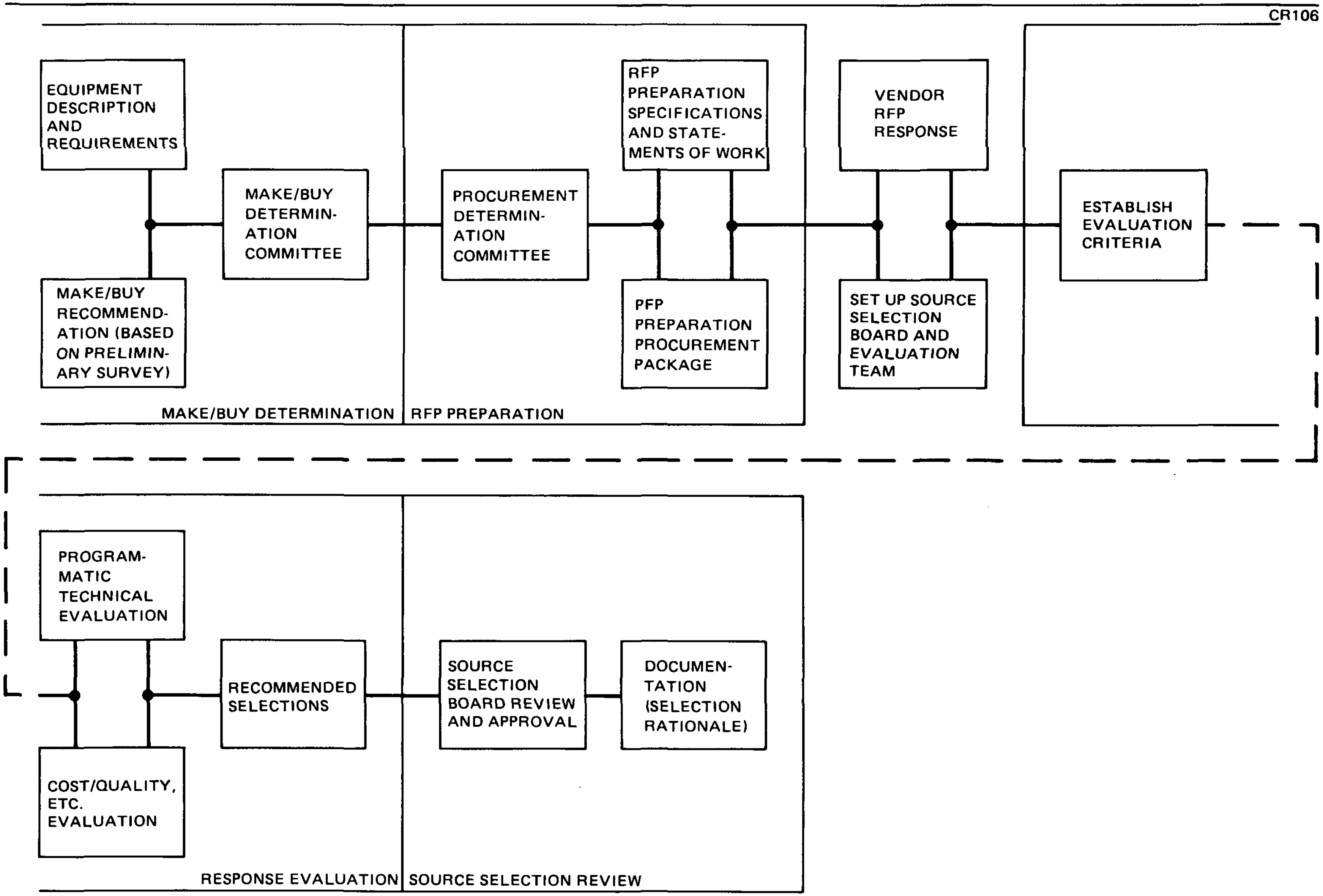

Figure 4-2. Source Selection Procedure

plus representation from propulsion technologies, quality assurance, costing, and procurement.

All positive responses were evaluated, with a quick elimination of bids not passing a set of "GO/NO-GO" criteria. Those proposals passing the "GO/NO-GO" rest were rated on their compliance with criteria shown in Table 4-2, as established by the evaluation team and approved by the Source Selection Board. The resulting source recommendations were presented to the Source Selection Board.

4.1.4 Source Selection

The results and recommendations of the evaluation were presented to the Source Selection Board for review, approval, and documentation of selection rationale and substantiation. All procurements were by fixed-price purchase order. Receiving/inspection was minimal and consisted of the following:

A. Purchased parts shall be received and all parts shall be counted, visually inspected, and checked for proper markings only at incoming inspection, in accordance with MDAC procedures.

B. Parts will be delivered directly to project management from receiving, where acceptance tests shall be performed.

C. Non-conforming articles will be handled per paragraph 4.5 of the Reliability and Quality Program Plans (Reference 5).

Component testing was accomplished as part of the test program.

4.2 COMPONENT DEVELOPMENT

The components used in the biowaste resistojet system fall into two categories: Off-the-shelf, and advance technology. Development procedures differed considerably, as discussed in the following subsections.

4.2.1 State-of-the-Art Components

These components are readily available and form the bulk of the system, and include valves, filters, etc. Table 4-3 shows the components selected source, source evaluation ranking, and number of requests and responses. However, some additional comments are in order.

Table 4-2

SOURCE SELECTION
TECHNICAL EVALUATION CRITERIA

STRUCTURE/SYSTEM ____________________

SUPPLIER ____________________

EVALUATOR ____________________ DATE __________

Item	Possible Score	This Score
I. DESIGN		
Concept Suitability/Acceptability		
Design Approach and Substantiation		
Reliability/Maintainability/Life		
Flight Adaptability		
General (weight, bosses, etc.)		
II. SUPPORT DATA		
Analysis and Test Data		
Use History of Similar Models		
III. OPERATIONAL		
Leakage (1×10^{-3} sccs He)		
Primary (flow, output)		
General (efficiency, media)		
IV. SUPPLY		
Schedule Compliance		
TOTALS	100	

Table 4-3

COMPONENT SELECTION

Component	Selection	Part No.	Tech. Ranking	Cost Ranking	Number of Requests	Number of Responses
Regulator	Tescom	26-1530-34	1	2	9	6
Latching VLV	Futurecraft	200487	4	1	9	6
Manual VLV	Tescom	30-1101-304	1	2	14	6
Fill/Drain VLV	Tescom	30-1301-308	1	1	14	6
Check VLV	Hoke	6231J45	2	1	14	4
Relief VLV	Hoke	6532L4Y 6548L4Y	3	1	14	4
Filters	Circle Seal	4210T-41T 43136-20TL	1	1	8	3
Water Pump	Micropump	12-40-316-208	1	1	7	2
Tanks-Gas	Tank Farm	--	1 Tie	1	9	4
Tanks-Water	H. B. Brown	WX204	1	1	9	3

Total number of companies = 51

Positive responses = 29

Regulator	-	Tescon provided vastly superior design. Cost of fittings for low bid exceeds the cost difference.
Latching Valve	-	Futurecraft design acceptable, low rating primarily due to lack of support data. MDAC has had good recent experience with Futurecraft with other products. Next low price was almost double.
Manual Valve	-	Estimated mounting cost for low bid is \$450, which exceeds delta cost. Also, small handle size (1-1/2 in.) makes usage difficult.
Check Valve Relief Valve	-	Hoke design acceptable, downgraded primarily for lack of support data. Good company experience with Hoke Products.

These components were purchased by supplier part number in the quantities required. Acceptance testing was done by MDAC for proof, leak, and basic performance (if necessary). The only exception was the Futurecraft latching valve which had quality assurance inspection for proof and leak included in their bid. Spot test for ΔP were conducted at MDAC, and a ΔP of less than 0.7×10^4 N/m^2 (1 psi) observed.

4.2.2 Advance Technology Components

This category included the water vaporizer and low- and high-pressure compressors. The source evaluation procedure was the same as for state-of-the-art components except more substantial support data was required, which was one of the most significant factors in evaluation (along with cost). These components had to pass demonstration tests (witnessed by MDAC) before shipping as well as pass the MDAC acceptance test program.

4.2.2.1 Water Vaporizer

Use of the presently developed evacuated concentric tube resistojet requires that propellants be injected as gases, not liquids (this may or may not be true of other concepts or advanced concentric tube designs). The heating capacity, heater geometry, and propellant stay times of this concept are not compatible with liquid propellants, and therefore some form of preinjection vaporization (or liquid flow control) is required. For the case of preinjection vaporization of water, this means that portions of the feed system

must be compatible with and capable of handling steam. The nominal resistojet chamber pressure is 4.28 - 5.35 x 10^5 N/m^2 (40 to 50 psia) and, after allowing for pressure drops, thermal losses, and a reasonable superheat margin, the system must have capability for handling 450°K (810°R) steam.

The key design specification requirements are:

A. Existing commercial standards
B. Media - H_2O with dissolved CH_4, CO_2, N_2, NH_3, O_2
C. Power - Standard 110 vac
D. Pressure 2 to 3 atm
E. Minimum power
F. Performance
   1. Flow - 0.09 x 10^{-3} kg/sec max steady state
      - 0.25 x 10^{-3} kg/sec max transient
   2. Outlet Temperature - 480 ± 22°K steady state
      - $480 \begin{smallmatrix} +22 \\ 55 \end{smallmatrix}$ °K transient
   3. Power - Minimize, design goal of 1,000 w

Additional requirements included the objectives of minimizing average and peak power, time to steady-state sequencing lead and lag times, and thermal control limits. Material compatibility, configuration, weight, cleanliness, reliability, and quality assurance provisions were included.

Responsibility for the vaporizer design and development was awarded to the Marquardt Company (TMC), whose design is based on a water vaporizer used in resistojet thrustor development testing (Reference 6). The design is shown in Figure 4-3 and is a scaled-up version of this proven concept and contains the following improvements/modifications:

A. Scale-up of capacity to comply with increased flow requirements.
B. Incorporation of a proportional power controller for automatic control of outlet steam temperature.
C. Optimization of thermal and hydrodynamic design based on prior test results.

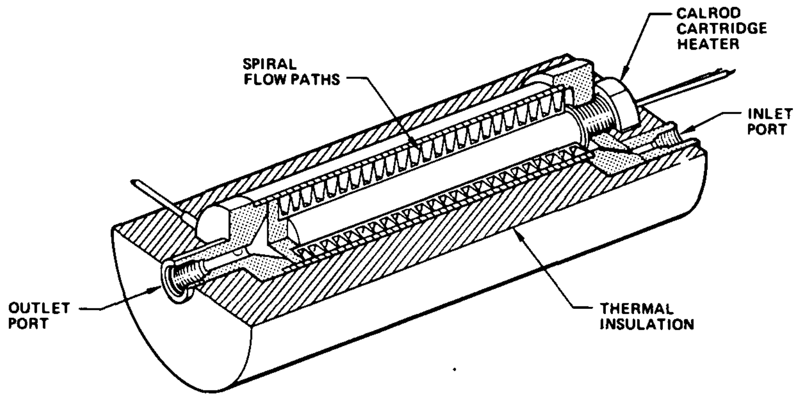

Figure 4-3. Water Vaporizer Design

One of the key aspects of the vaporizer design is the maximum dissipation of the heat from the cartridge heater and subsequent efficient heat transfer to the flowing media. This aspect is obtained in this design by precision fitting of the heater into finned copper tubing. The area of the finned tubing decreases the watt density of the heater from approximately 0.93×10^5 w/m^2 60 w/in.^{2}) to less than 0.124×10^5 w/m^2 (8 w/in.^{2}) which provides an excellent factor of safety for long-term application. The spiral passage gaps between the fins are filled with quasi-spherical-shaped Poro-Bond copper material and are integrally bonded with the finned copper tubing to assure positive contact between all elements, enhance the overall heat transfer characteristics, provide reduction in overall weight/size, and improve reliability characteristics.

Assembly of the water vaporizer consists of precision-fitting the cartridge heater into the heat exchanger assembly which is, in turn, installed in a stainless-steel casing. Min K 503 encases the entire assembly to reduce

power radiation losses. The heater has a nickel-chrome resistance element wound externally around a ceramic core. This resistance element is in close proximity to the sheath to achieve maximum heat transfer, but insulated from the sheath by magnesium oxide filler. Characteristics of the heater are:

A. Wattage: 1, 100 w (max)

B. Voltage: 115 vac, 60-cycle

C. Case Material: Inconel

D. Manufacturer and P/N: Chromalox C1-505R

The cartridge heater temperature is sensed at the module outlet end by a temperature probe. The output from this temperature probe is fed directly to the power controller, which regulates the power to the heater to maintain the output steam temperature within its specified tolerance. The power controller is a proportional solid-state device, manufactured by Oven Industries and is used to maintain the output steam temperature within the specified tolerances. Minor modifications have been made to the Oven Industries commercial Model 5CX controller to provide for unique gain characteristics and adjustments for specific optimization of the thermal control characteristics of the water vaporizer for this application. The controller operational schematic is shown in Figure 4-4. The power-versus-temperature-gain characteristic is specifically tailored to the requirements of this application so that as the desired operating conditions are approached, the power is gradually modulated so that the normally experienced temperature overshoots and undershoots are greatly reduced. In addition, this particular power controller provides (1) adjustable gain characteristics and set-point so that the controller can be tuned to the specific thermal characteristics of the water vaporizer to optimize the system's overall thermal response characteristics, (2) complete coverage of the flow ranges specified without using more complicated approaches such as a multiple heat heater with associated relay switches for various modes of operation or multiple engine operation, and (3) increased heater reliability by gradually modulating the power requirements rather than on-off cycling or the more rapid changes which occur with a non-proportional and/or high-gain characteristic controller.

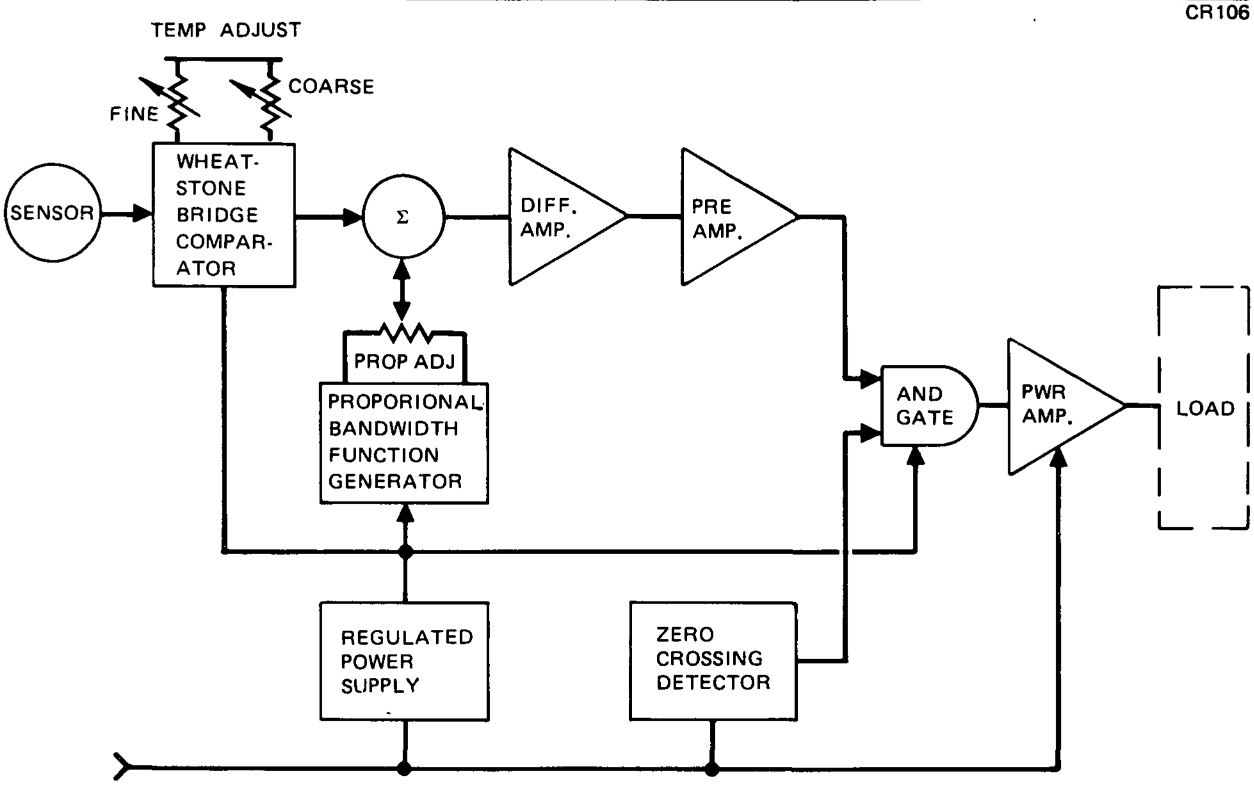

Figure 4-4. Temperature Controller Block Diagram

TMC tested the breadboard unit at various control settings and flow rates. The results met requirements, but show that actual outlet temperature does not reach 480°K (860°R) even though the heater is maintained at a constant 480°K (860°R) temperature by the controller, although this difference is small. Furthermore, during the MDAC tests, outlet temperature only reached 455°K (820°R) at the 8,840 (480°K) setting, which may be due to several inches of uninsulated line between the vaporizer outlet and the temperature probe. This is only marginally acceptable, but increasing the setting to 9,500 raised the steam temperature to 470°K (850°R). Oven Industries lists the temperature/control setting as follows:

Setting	Temperature
5,795	435°K (780°R)
7,195	460°K (830°R)
8,840	480°K (860°R)

The 9,500 setting should result in a control temperature of about 485°K (870°R). Actual setting in the system will depend on insulation and/or

line heater effectiveness. Figure 4-5 shows a typical test run. The 3- to 4-min pre-heat period assures single-phase-steam start transient when water flow is initiated.

4.2.2.2 Low-Pressure Compressor

The requirement to compression-pump the EC/LS gases for efficient storage has been established as part of the baseline resistojet system design concept. However, EC/LS differences between the CO_2 and CH_4 interface characteristics require sophisticated mechanization. These differences are summarized as follows:

Gas	Pressure	Availability
CO_2	$2.15 - 2.9 \times 10^5$ N/m^2 (31 to 42 psia)	Intermittent – Controlled from EC/LS accumulator
CH_4	$1.08 \pm 0.036 \times 10^5$ N/m^2 (15.5 ± 0.5 psia)	Continuous – No EC/LS accumulator

There are several important design factors that must be considered in selecting a collection concept. These are CO_2/CH_4 commonality, flow capacity concept practicality, and cooling (compression heat). Basically, it is difficult to scale down pumps to these flow rates, to provide 20:1 compression without multistages or cooling, and to produce the commonality desired to minimize development cost and simplify maintenance and spares requirements.

The design concept selected achieves these results by including a low pressure ratio compressor (2.7:1 compression ratio) and accumulator in the CH_4 line, operated continuously to keep the accumulator filled. This then, allows a common, high ratio (10:1) compressor to be used for each propellant for efficient storage. This subsection documents development of the low pressure compressor (LPC).

The key design-specification requirements were:

A. Existing commercial standards acceptable
B. All materials compatible with methane (CH_4)

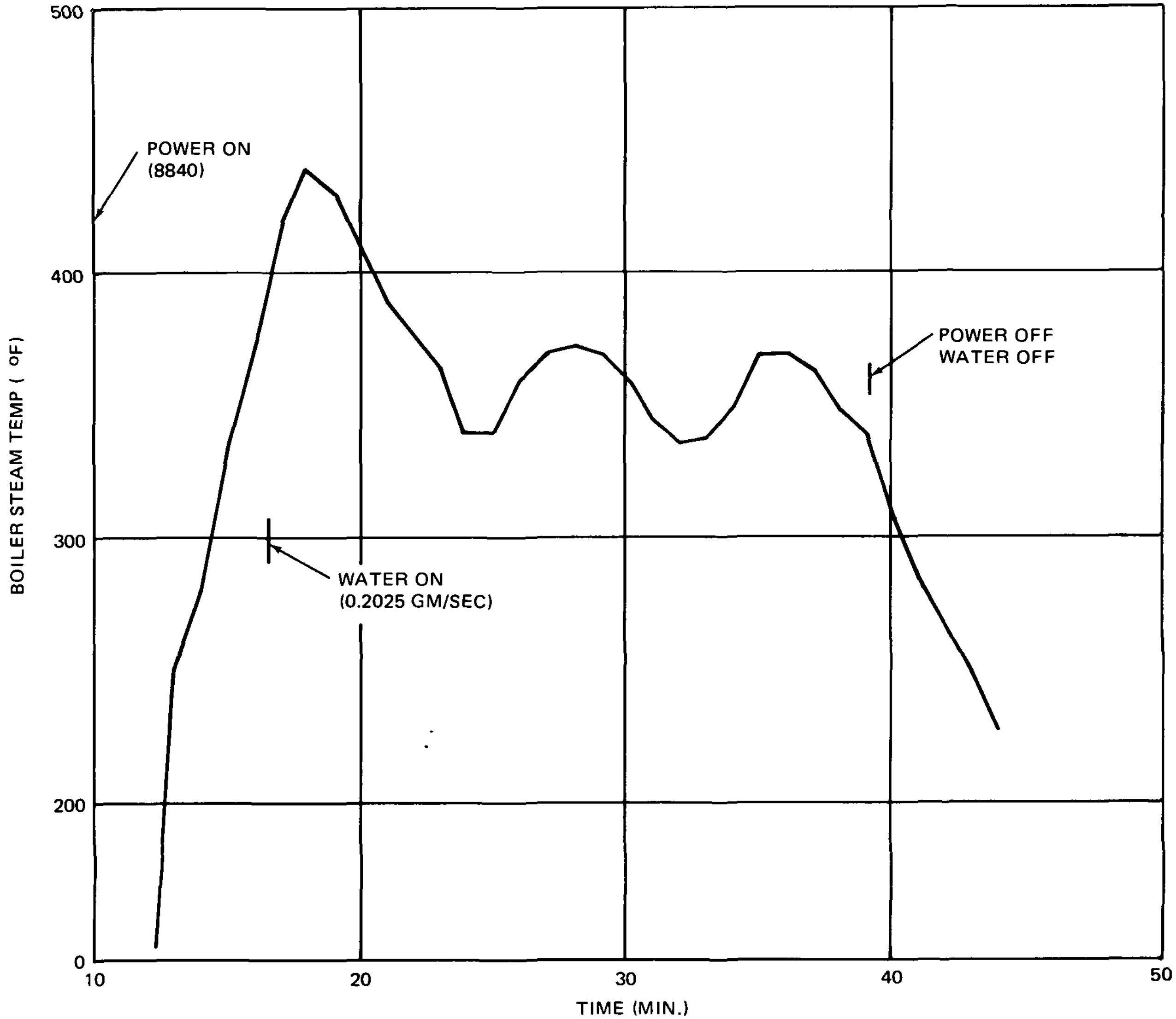

Figure 4-5. Water Vaporizer Temperature History

C. Power source

1. 24 vdc
2. 120 v, 60-cycle, one-phase
3. 108/210 v, 400-cycle, three-phase

D. No special cooling requirements

E. Oil-free lubrication

F. Performance

1. Flow — 0. 1 scfm
2. Pressure ratio — 2. 7:1
3. Maximum outlet pressure — 2. 9 x 10^5 μ/m^2 (42 psia)
4. Duty cycle — continuous
5. Power — 0. 1 hp.

Responsibility for the compressor development was awarded to Metal Bellows Co. (MBC), and the significant design features were:

A. Motor - Task motor No. 5380-3 (1/4 hp) with a 201-size bearing for added life.

B. Stroke = 0. 0085 m (0. 30 in.).

C. Estimated motor speed is 3, 720 rpm.

D. The actual cfm capacity required at a 340 °K (610 °R), 1.08 x 10^5 N/m^2 (15. 5 psia) is 0. 109 cfm.

E. Torque to overcome spring force of bellows is 0. 006 m/kg (1. 22 in. /lb).

F. Isentropic compression power for k = 1. 3 (Pv^k) and inlet conditions of 1. 08 x 10^5 N/m^2 (15. 5 psia) pressure and 0. 744-cfm flow is calculated at 0. 0566 hp. Applying 50 percent efficiency, the motor power requirement should be at least 0. 112 hp.

G. Whirl frequency of counterweight was calculated to be 1, 700 Hz which was much greater than frequency of motor shaft rotation— no problem with overhung shaft.

H. A stroke of 0. 0077 m (0. 300 in.) was selected to provide a minimum of 0. 1 scfm flow at a discharge pressure of 2. 9 x $10^5$$N/m^2$ (42 psia).

The resulting design is shown in Figures 4-6 and 4-7.

The 0. 25-hp task motor (No. 5380-3) selected for the job was somewhat oversized but was readily available. This approach carried the least risk in delaying compressor delivery.

CR106

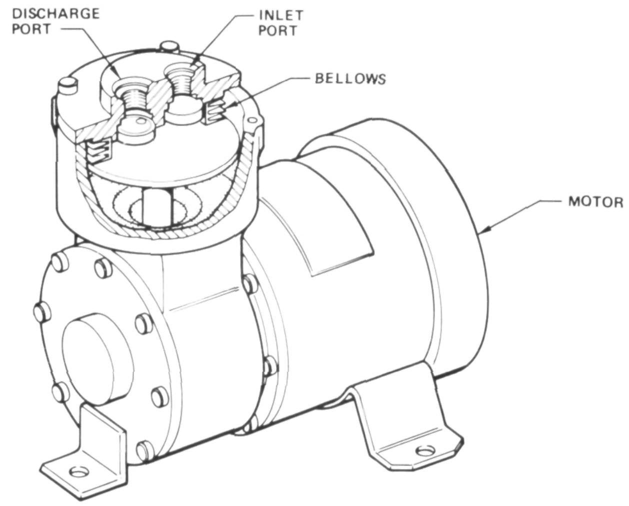

Figure 4-6. Low-Pressure Compressor Design

CR106

Figure 4-7. Low-Pressure Compressor

A 201-size motor bearing was finally selected to give a minimum bearing life of 9,500 hr. This was the largest size bearing that would fit in the motor cap and yet leave room for the motor protector.

The compressors performed quite satisfactorily with a 0.0077-m (0.300-in.) stroke and the shaft power, which corresponds to 1.3 amp is 0.17 hp. Acceptance tests of all three units were conducted at both Metal Bellows and MDAC. All test runs at both facilities demonstrated compliance with specification requirements. However, MBC data shows the S/N 3 compressor had performance parameters significantly lower than S/N 1 and 2. This is felt to be either slightly larger clearance volume or slightly shorter stroke. However, since all tests were within specifications, no additional action was taken.

Figure 4-8 shows MBC test data flow capacity as a function of run time and the MDAC design point. The difference between the MBC and MDAC test data is due to test setup differences. MBC used 3/8-in. outlet lines and left the inlet port open to ambient. MDAC used 1/4-in. outlet lines (simulating the actual system) and supplied GN_2 regulated at 15 psia to the inlet. Also, MDAC used no inlet plenum to ensure smooth, continuous flow to the compressor.

4.2.2.3 High-Pressure Compressor

The contract for the high-pressure compressor (HPC) was also awarded to Metal Bellows for a bellows compressor of the same type as their low-pressure compressor. The key design specification requirements were:

- A. Existing commercial standards acceptable.
- B. All materials compatible with methane (CH_4) and carbon dioxide (CO_2)
- C. Power source (choice)
  1. 24 vdc
  2. 120 v, 60-cycle, single-phase
  3. 108/210 v, 400-cycle, three-phase
- D. No special cooling requirements
- E. Oil-free lubrication
- F. Performance
  1. Flow—0.5 scfm
  2. Pressure ratio—10:1

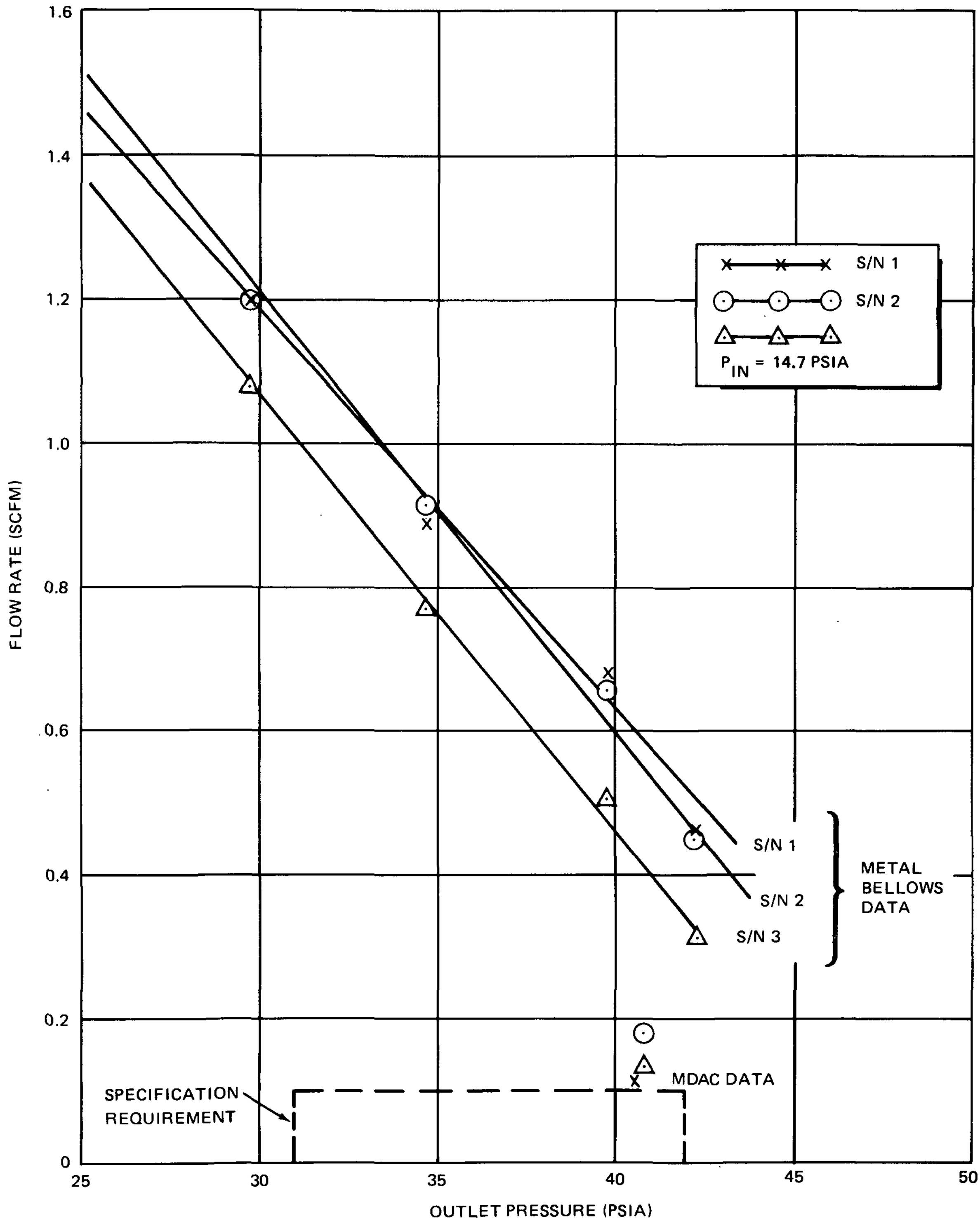

Figure 4-8. Low-Pressure Compressor Flow Rate vs Pressure

3. Max outlet pressure—2.14 x 10^6 N/m^2 (300 psia)
4. Duty cycle—intermittent (3 min. on, 50 min. off)
5. Power—0.5 hp.

The significant design features of this compressor design over standard commercial versions of single-stage, bellows compressors are, as follows:

- Three pump stages are employed to reach the 10:1 compression ratio.
- Operation at a relatively high discharge pressure of 2.14 x 10^6 N/m^2 (300 psia) required use of a pressurized crankcase to reduce the maximum pressure differential across the Stage III bellows. Bellows stress levels are low enough to provide long life by eliminating metal fatigue.
- The sealed crankcase also serves as a containment chamber in case a bellows of any stage did fracture.
- The design package is compact and utilizes a 12-pole, three-phase 400 Hz motor for flight use in aircraft or space vehicles.

The compressor design as shown in Figures 4-9 and 4-10 consists of three pumping chambers interconnecting by hardline plumbing. The gas is taken into Stage I and raised in pressure in sequence to achieve discharge pressures from Stage III in excess of 2.14 x 10^6 N/m^2 (300 psia). The crankcase is sealed by O-ring seals and charged to 1 x 10^6 N/m^2 (140 psia) static pressure at room temperature. The design pressures used to size the compressor with respect to bearing loads, diaphragm pressure stress, and starting torques are:

Inlet Pressure	- Stage I	2.14 x 10^5 N/m^2	(30 psia)
Discharge Pressure	- Stage I	5.5 x 10^5 N/m^2	(80 psia)
Discharge Pressure	- Stage II	1.0 x 10^6 N/m^2	(140 psia)
Discharge Pressure	- Stage III	2.14 x 10^6 N/m^2	(300 psia)
Crankcase Charge Pressure		1.0 x 10^6 N/m^2	(140 psia)

The two main shaft bearings and three driver-rod bearings are single-row, radial, deep-groove-type ball bearings permanently lubricated with grease for the life of the compressor. Shields are employed to contain grease in the bearings but to avoid the lip seal friction of sealed ball bearings. The motor rotor is overhung without the use of a shaft supporting bearing in the motor cover. A motor protector (with automatic reset) and hermetic electrical

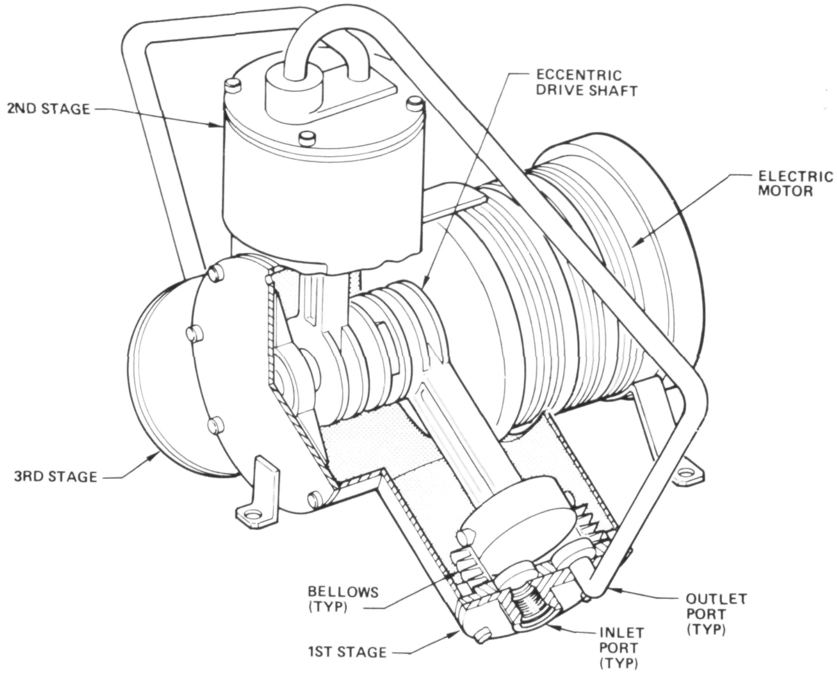

Figure 4-9. High-Pressure Compressor Design

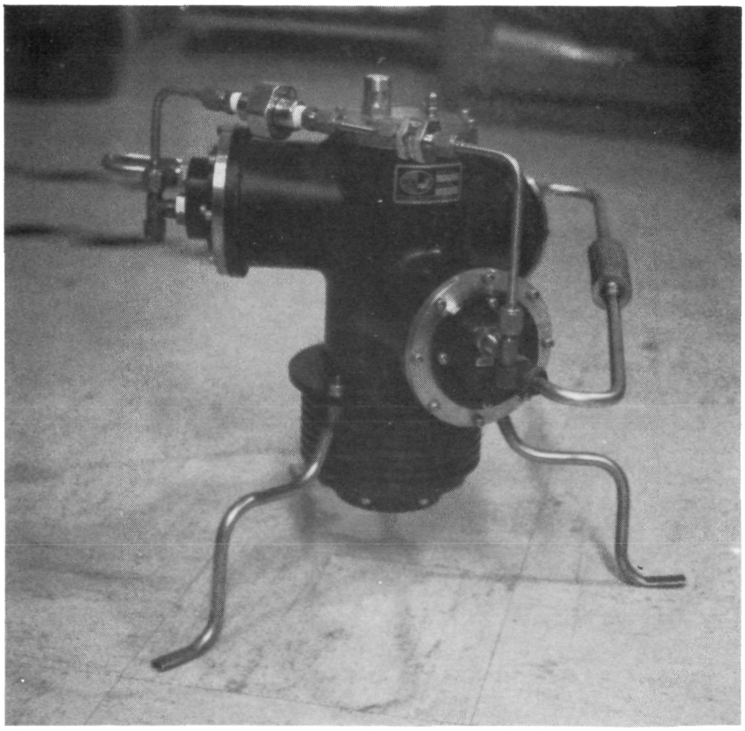

Figure 4-10. High-Pressure Compressor

connector are mounted to the motor cover. Compressor valves are of the reed type with PTFE gaskets for static sealing.

The important characteristics of the drive motor are as follows:

Power Supply:	three-phase, wye, 200 v phase-to-phase, 400 Hz
No Load Speed:	4,000 rpm (12-pole)
Shaft Power:	0.38 hp @ 3,700 rpm (continuous duty)
Locked Rotor Torque:	0.11 N-m (150 in.-oz) min

The problem of starting the compressor under the conditions of (1) full crankcase pressure of 1.0×10^6 N/m^2 (140 psia), and (2) ports open to atmospheric pressure was solved by having Stages II and III stroke 180 deg out of phase to Stage I. This feature, together with the fact that the combined effective areas of Stages I and II are nearly equal to the effective area of Stage I bellows, produces a relatively low starting torque requirement of 0.042 N-m (57.6 in.-oz). (See Table 4-4.) Since this value is less than the 0.11 N-m (150 in.-oz) provided by the motor, the drive train will accelerate when the motor is energized.

However, it was still necessary to devise an unloader when restarting the compressor against an upstream pressure. When the compressor is shut down, the bypass line reduces the pressure between the discharge port and a system check valve by bleeding gas through a 0.005-in. orifice to the compressor input port. Once the pressure difference between discharge and intake ports is less than 2.14×10^5 N/m^2 (30 psi), the compressor will start. A 2-min minimum time interval was required to reduce the differential from 19.4-2.15 x 10^5 N/m^2 (270 to 30 psi). This time interval was not objectional because the duty cycle includes a 50-min "off" time.

The final HPC design operates at a relatively low noise level with a minimum of mechanical vibration. The preliminary testing completed to date indicates that the active bellows in the compressor are operating in the infinite life range (greater than 10^7 cycles) and hence the predicted life of the final design is within the original design limitations.

Table 4-4

TORQUE REQUIREMENTS

	ΔP	EA	S	Ts
Stage I	125 psi	3.648 in.^{2}	0.250 in.	50.2 in./lb
Stage II	125 psi	2.178 in.^{2}	0.250 in.	-29.9 in./lb
Stage III	125 psi	2.178 in.^{2}	0.200 in.	-23.9 in./lb
			TOTAL =	-3.6 in./lb (-57.6 in./oz)

This compressor design has been tested for more than 80 hr total and 40 hr of continuous operation using ambient air and pressurized GN_2 for test media. Although compressors with such low flow rates are usually not very efficient, an overall efficiency of 43 percent and a compressor efficiency of 62 percent was obtained when tested in the normal configuration (with the interstage bleed orifice installed).

Figure 4-11 shows actual test data for the first compressor shipped. The specification requirement of 0.5 scfm gas flow was reached with a suction pressure of 2.15×10^5 N/m^2 (31.0 psia) and a discharge pressure of 2.14×10^6 N/m^2 (300 psia). Suction pressure levels have a strong effect on changes in throughput and motor input power. Subsequent compressors had smaller clearance volumes, and were able to meet the 0.5 scfm flow at 2.15×10^5 N/m^2 (80 psia) suction with 2.14×10^6 N/m^2 (300 psia) discharge.

The compressor as designed must be cooled with forced air for continuous operation. Free convection in air is sufficient for the intermittent duty of 3 min "on" and 50 min "off."

4.3 CONTROL CONSOLE DESIGN AND DEVELOPMENT

The control console provides the electronics for the following functions:

A. Power Supply
B. Relay and Relay Driver
C. Operational Sequencers
D. Manual Component Control
E. System Status Display

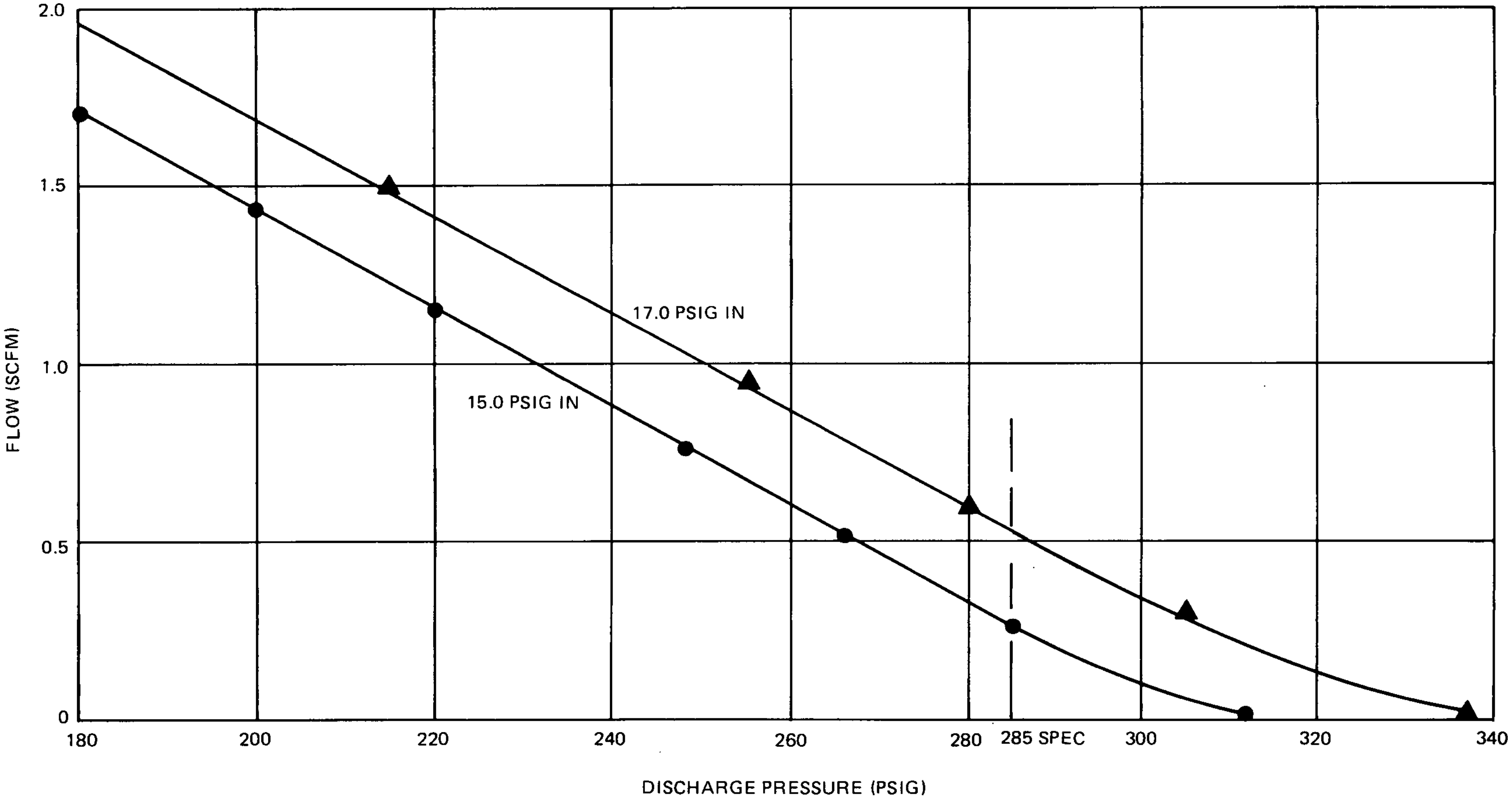

Figure 4-11. High-Pressure Compressor Flow Rate vs. Pressure

Its design and operation are explained in the following subsections:

4.3.1 Console Design

The resulting console is shown in Figure 4-12. The front panel is a schematic of the system showing the valves and compressors operated from the console. A timing display at the top shows the master sequencer running time. The two power supplies at the bottom are a 5-v supply (TRYGON model No. M3P8-250V) for sequencer operation, and a 28-v supply (TRYGON model No. L5R28-30) for system relay operation.

Toggle switches are provided for each component and sequencer. The latching valves use momentary switches that automatically return to the AUTO position to prevent power from being continuously applied to the valves, which are designed for only instantaneous signals (≈ 100 ms). The compressors, heaters, and vaporizer are three-position switches permitting sequencer operation in the AUTO position, but with on-and-off override capability. The sequencer switches are two position: on (enable) and off (stop). A master reset switch to reset all sequencers to zero is also provided.

Also included on the front panel schematic are component status (indicator lights: lighted for on or open, dark for off or closed. Since none of the components has position feedback mechanisms, position memory circuit cards were designed which use the component command signals to activate/deactivate the indicator lights.

Relay and relay driver circuit cards were sligtly modified from an existing design to match resistojet system characteristics.

4.2.3 Sequencer Design and Operation

The system sequencer design involves three separate circuits cards: clock, sequencer, and event detection. Basically, the clock card transforms the 110 vac, 60-cycle input power into two counting pulse rates of 1 and 10 pulses per sec. The sequencer counts these pulses sequentially and provides a signal at each interval of operation (each second or tenth of a second). The event detection provides the operational command at the appropriate time to the appropriate component.

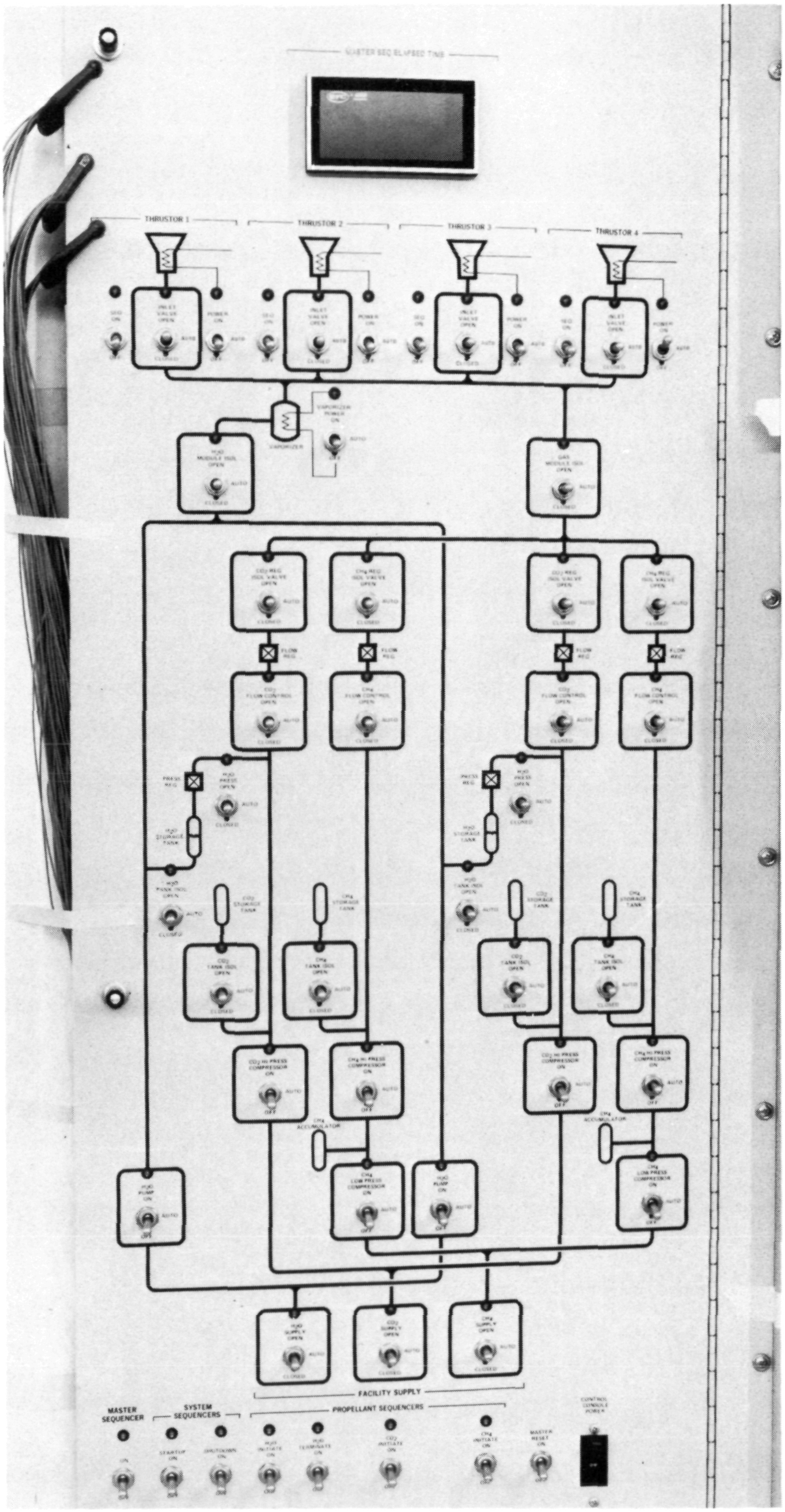

Figure 4-12. Resistojet System Control Console

4.3.2.1 Clock

The clock card converts the 60-cycle input power into 10-pulse-per-sec and 1-pulse-per-sec pulse trains. Provisions are made to insure adequate noise suppression etc.

4.3.2.2 Event Detection

Each event detection board consists of ten events that can be programmed for the desired time of occurrence. The output of each gate is hard-wired to a relay driver for the component to be activated/deactivated. Each event detection board is connected to a particular sequencer.

In designating the circuit for this card, it was determined that a double-sized card would be required if all ten events were to be on one board. The use of a double-sized card also avoids connector pin limitations. Five of the ten events are provided with memory capability, with the remaining five events resetting the memory. This memory provision is acquired for equipments requiring a continuous signal, such as the compressors and vaporizer. All patching of event times is done using miniature patch cards. Each event has the capability of being enabled or inhibited by an additional control signal (not used at present, but available if required). Provisions for expanding the number of additional control signal inputs is provided for each event detection gate. Program patching of this board is done as follows: A typical event detection card is shown in Figure 4-13, and should be oriented so that the connector end is on the bottom and the pins are facing the observer. The section of decoded time lines representing the most significant digit is then located on the left and events are numbered 10 through 1 from top to bottom. The card may be divided into five sections, four of which are identical, while the fifth, located in the center, is functionally distinct. Each of the four sections consist of ten ten-pin columns of decoded time lines alternated with ten five-pin rows of event gate input lines. To program the time at which an event is to be detected, the row of pins corresponding to the selected event should be located. Then, using the miniature patch cards, pins on this row should be connected to the appropriate decoded time line on each of the four sections. The patch system is designed so that only one patch card length is required, by spacing an event gate input pin one patch length away from every time line pin. The center section is used to program the reset of the

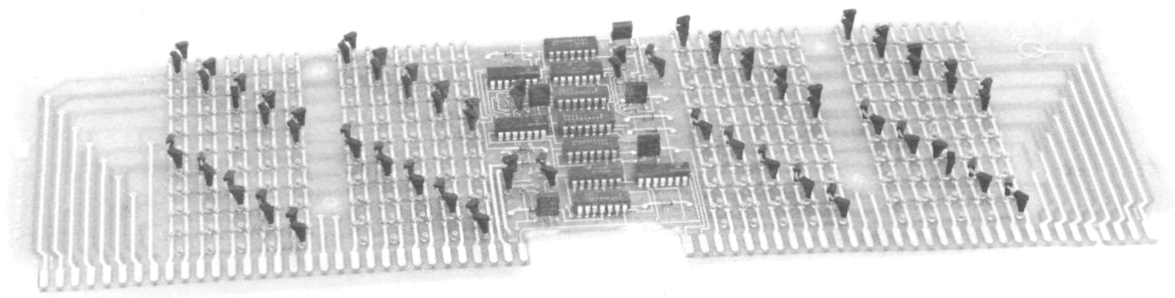

Figure 4-13. Event Detection Board

five memory elements on the event detection card. For example, if it is desired that the flip flop (FF) associated with Event 1 should be reset by Event 2, then a patch cord should be connected between the flip flop and Event 2. Otherwise, the input to the FF should be patched to ground through the adjacent pin. Four similar patches are required for Events 4, 6, 8, and 10, which control the reset of the memory elements associated with Events 3, 5, 7, and 9, respectively. The event detection cards are mounted vertically in the cabinet and are alternated with their associated sequencers to form a single row of cards. Hardwiring of the gate outputs is shown in Table 4-5.

4.3.2.3 Sequencer

The sequencer board is the heart of the automatic system control. It counts clock pulses and at each count sends a signal to the event detection board. All sequencers are identical, and are double-sized because of the connector pin limitations. Counting is done in BCD and the BCD to ten-line conversion is also done on this card. The BCD outputs are brought off the card so that the main Sequencer timing can be displayed. Each is provided with two reset (one master) inputs and start/stop control inputs, and has capability for two

Table 4-5

EVENT DETECTION GATE ASSIGNMENTS*

Sequencer No.	Output Gate No. 1	2	3	4	5	6	7	8	9	10	11-20
1 (Master)	System Start Sequencer Enable	CH_4 Start Sequencer Enable	CO_2 Start Sequencer Enable	H_2O Start Sequencer Enable	H_2O Stop Sequencer Enable	Thrustor Sequencer Enable (All Four)	Compressor Activation (All 6) (Memory)	Compressor Deactivation (All 6) (Memory Reset)	--	--	12-15: Repeat 2-5 19. Syst Stop 20. Reset
2 (System Start)	Open Valves 1, 2, 7, 8, 13, 14	Open Valves 5, 6, 11, 12, 15, 16, 23, 24, 25		Open Valve 17	--	--	--	--	--	Reset	N/A
3 (System Stop)	Close Valves 3, 4, 9, 10, 22-25 Open Valves 13, 14	Close Valves 5, 6, 11, 12	Close Valves 1, 2, 7, 8, 15-16	--	--	Close Valves 17, 18	--	--	--	Reset	N/A
4 (CH_4 Start)	Close Valves 9, 10 Open Valves 1, 2	--	Open Valve 17	Open Valve 3	Open Valve 4	Close Valve 18	--	--	--	Reset	N/A
5 (CO_2 Start)	Close Valves 3, 4 Open Valves 7, 8	--	Open Valve 17	Open Valve 9	Open Valve 10	Close Valve 18	--	--	--	Reset	N/A
6 (H_2O Start)	Close Valves 3, 4, 9, 10 Open Valves 13, 14, 15, 16	--	Close Valve 17	Open Valve 18	Turn on Vaporizer (Memory)		--	--	--	Reset	N/A
7 (H_2O Stop)	Close Valves 13, 14	Close Valve 18	Not Available	Turn Off Vaporizer (Memory Reset)	--	--	--	--	--	Reset	N/A
8-11 (Thrustors)	Turn On Thrustor Heater (Memory)	Turn Off Thrustor Heater (Memory Reset)	Open Thrustor Valve	Close Thrustor Valve	REPEAT OF EVENTS 1 - 4					Reset	N/A

*See continuation page for nomenclature

Table 4-5

EVENT DETECTION GATE ASSIGNMENTS (Continued)

NOMENCLATURE

Sequencers (11)		Compressors (8)	
1.	Master	1.	H_2O Pump 1
2.	System Start-up	2.	H_2O Pump 2
3.	System Shutdown	3.	CH_4 Blower 1
4.	CH_4 Start-up	4.	CH_4 Blower 2
5.	CO_2 Start-up	5.	CH_4 Compressor 1
6.	H_2O Start-up	6.	CH_4 Compressor 2
7.	H_2O Shutdown	7.	CO_2 Compressor 1
8.	Thrustor 1	8.	CO_2 Compressor 2
9.	Thrustor 2		
10.	Thrustor 3		
11.	Thrustor 4		

Valves (25)		Heaters (5)	
1.	CH_4 Tank Isolation 1	1.	Vaporizer 1
2.	CH_4 Tank Isolation 2	2.	Thrustor Heater 1
3.	CH_4 Flow Control 1	3.	Thrustor Heater 2
4.	CH_4 Flow Control 2	4.	Thrustor Heater 3
5.	CH_4 Regulator Isolation 1	5.	Thrustor Heater 4
6.	CH_4 Regulator Isolation 2		
7.	CO_2 Tank Isolation 1		
8.	CO_2 Tank Isolation 2		
9.	CO_2 Flow Control 1		
10.	CO_2 Flow Control 2		
11.	CO_2 Regulator Isolation 1		
12.	CO_2 Regulator Isolation 2		

Notes:

1. Water system heaters will be included, if required.
2. Signals to thrustor valves, thrustor heaters and facility valves will be provided; however, the actual components are excluded.
3. All valves magnetic latching.
4. All compressors and heaters require continuous power.

Table 4-5

EVENT DETECTION GATE ASSIGNMENTS (Continued)

NOMENCLATURE

	Valves (25)
13.	H_2O Tank Isolation 1
14.	H_2O Tank Isolation 2
15.	H_2O Pressurant Inlet 1
16.	H_2O Pressurant Inlet 2
17.	Module Isolation - Gas
18.	Module Isolation - Water
19.	Thrustor Inlet 1
20.	Thrustor Inlet 2
21.	Thrustor Inlet 3
22.	Thrustor Inlet 4
23.	Facility CO_2
24.	Facility CH_4
25.	Facility H_2O

additional programmed start/stop inputs. The circuit implementation results in an extra inverter and three extra two input gates, which are included on the board and are available for future system change capability.

This Sequencer design is shown in Figures 4-14 through 4-16. Figure 4-14 shows the overall design; Figure 4-15 the event decode gate patch scheme; and Figure 4-16 the gate design. The linkage between the figures is as follows: In Figure 4-14 the SN 7442 outputs are the four groups of ten lines of Figure 4-15. These activate the event gates, of which a typical gate is shown in Figure 4-15. This gate controls the event as shown in Figure 4-16. The output of this gate can be wired directly to the desired function (no memory) or

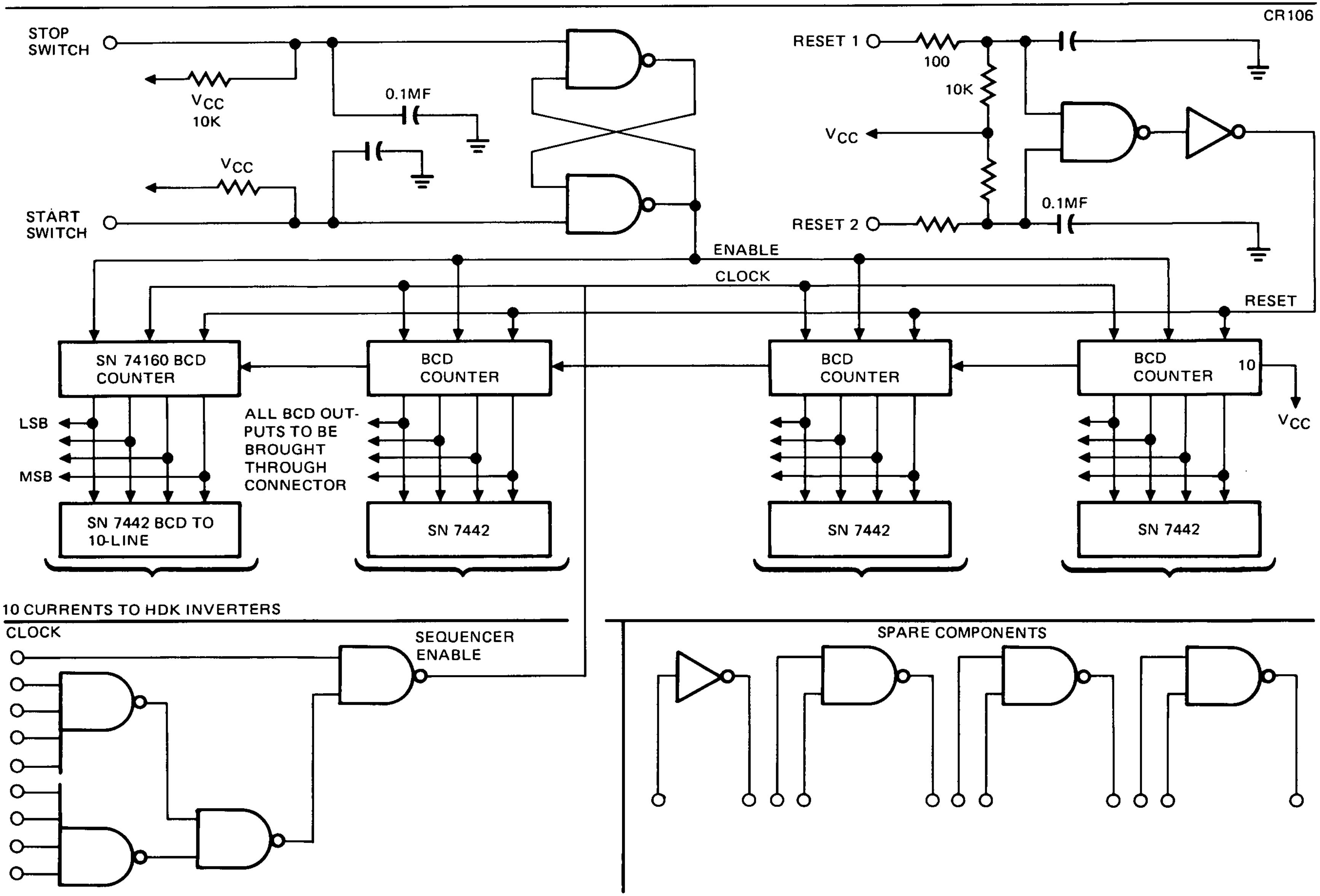

Figure 4-14. Resistojet Sequencer Design

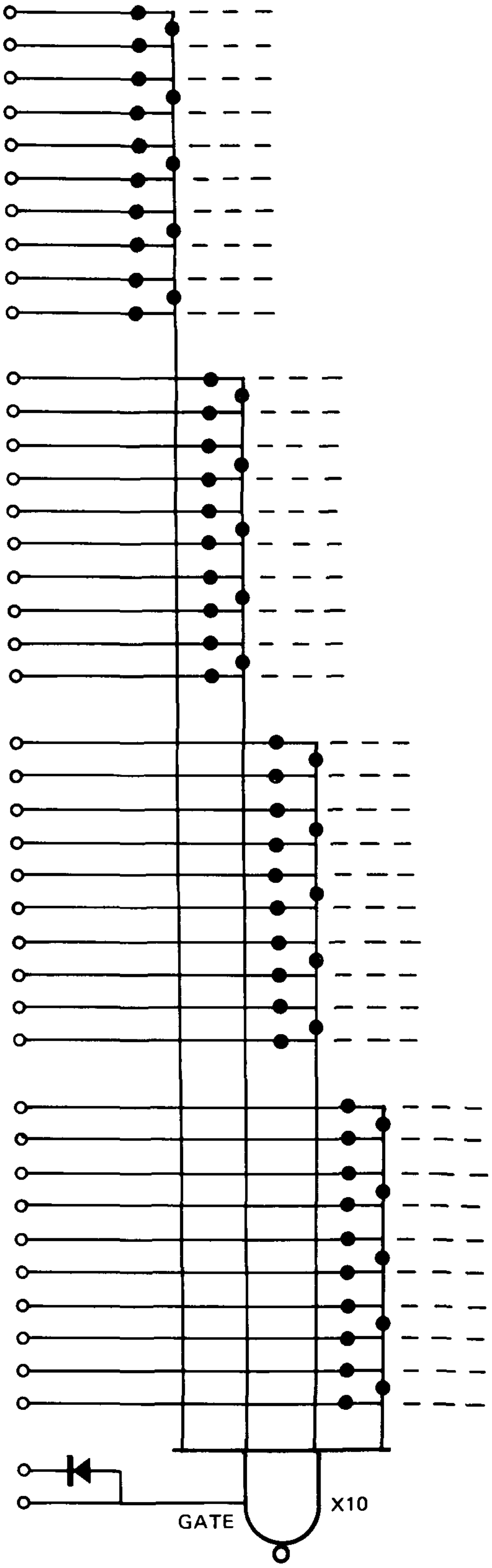

Figure 4-15. Typical Sequencer Event Decode Gate

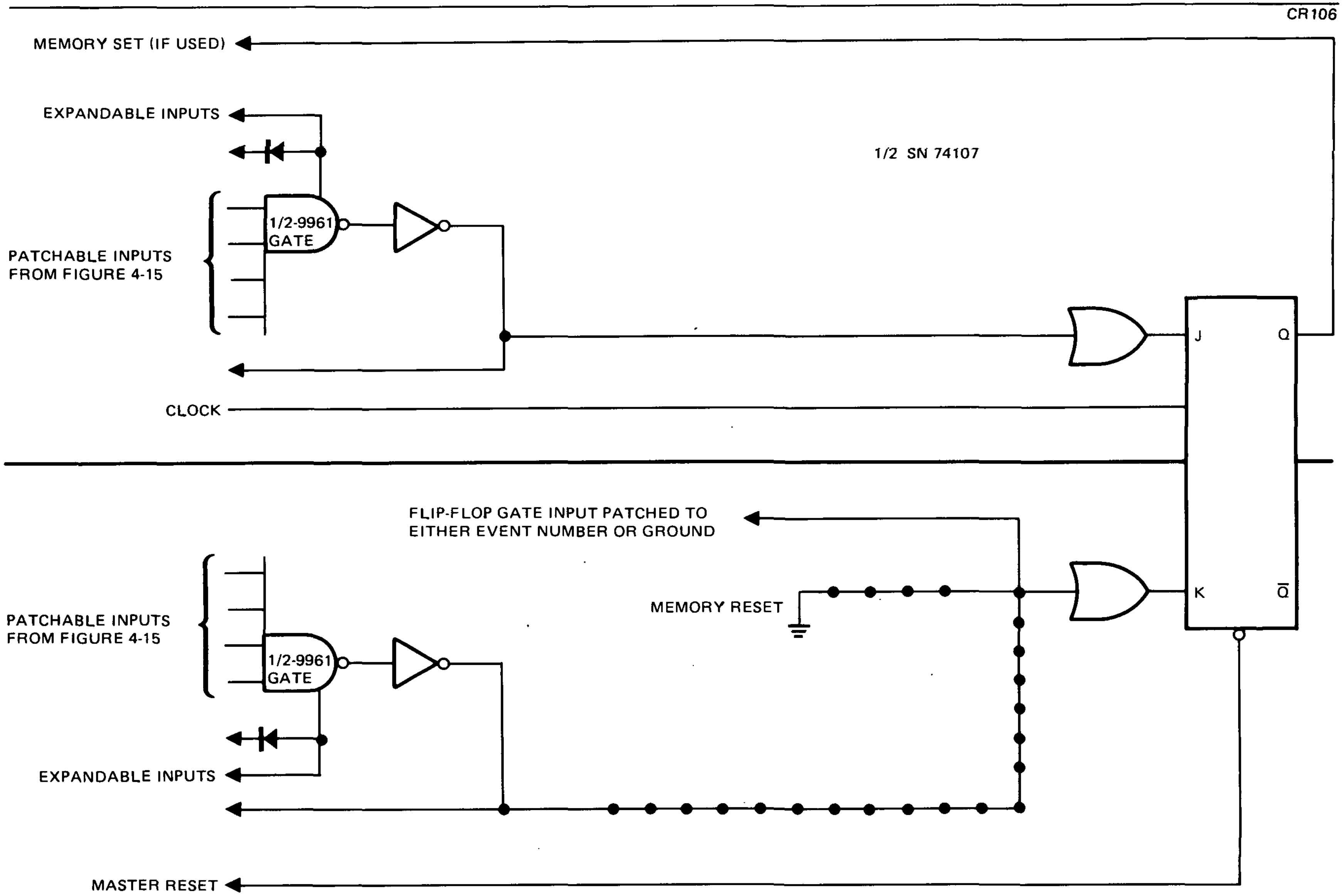

Figure 4-16. Gate Description Schematic

to be used to set the memory for functional control. When this capability is used (such as for thrustor firing), the second gate is used to reset the memory, or, in effect, "turn off" the function.

4.3.3 Test and Operation

Each individual circuit card was checked following manufacturing for continuity and performance. After all cards were installed, the console was checked out with a representative system timeline.

Operation is straightforward. The master reset is turned on to insure all sequencers starting at time zero, the components to be sequencer are placed in the auto position, slave sequencers in the on position. To start operation the reset is turned off and master sequencer turned on.

4.4 MECHANICAL SUBSYSTEM DESIGN AND DEVELOPMENT

The mechanical system consists of two storage and feed assembly skids and a thrustor module. This ground test system, like the flight system, provides parallel, redundant storage and feed systems. Each system contains CO_2 and CH_4 compressors, storage tanks, regulators and valving plus a water tank, water pressurization assembly and flow control valving. These systems are manifolded upstream of a typical thrustor module consisting of four thrustors, water vaporizer, and valving. A bypass line from upstream of the pumps to downstream of the regulator is also provided. Each system is mounted on a movable skid type base, and includes a flow component panel, which has components mounted on the backside with the manual valve handles, regulator handle and pressure gauges on the front.

4.4.1 Storage and Feed Assembly

The schematic of the storage and feed assembly was shown in Section 3. Since the technicians were under the direct control of program management, no formal layout drawings were prepared, although a sketch of the component panel was made for drill holes. The panel is 1.2 m x 1.9 m (4 by 6 ft) sheet aluminum, with holes drilled for component mounting and is shown in Figure 4-17 following component installation. Also displayed (schematically) on the panel are compressor, tank, and latching valve locations and system plumbing.

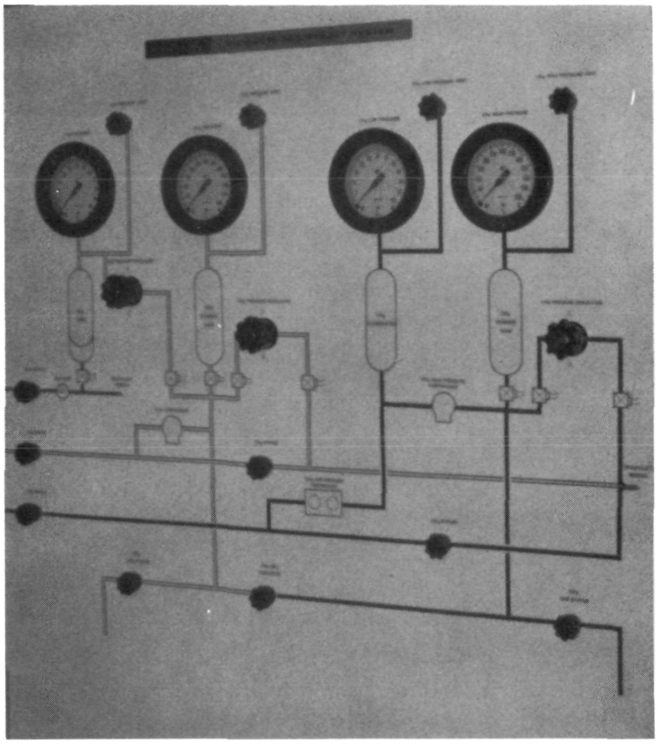

Figure 4-17. Component Panel

The panel is located at the front of the skid with the compressors located on the skid base immediately behind the panel. This whole first portion is framed with aluminum bar stock. The tanks are then placed toward the rear of the skid. Figure 4-18 shows the tank arrangement and part of the plumbing frame. The skid is a Martin Marietta (formerly Harvey Aluminum) standard skid assembly. Following panel mounting to the frame and tank installation on the skid, the compressors, pumps, and pressure switches were mounted to the back of the panel or frame. Plumbing was then routed, per the schematic, on a most convenient basis.

The electrical wiring from the console and facility power source plugs into a junction box at the back of the skid. This box also contains noise suppression diodes, "Power on" indicator lights and a safety switch that automatically shuts off power when the box is opened. A sketch of the wiring layout for this box was prepared, with final wiring in the box and from the box to the components routed in conformance with good engineering practice. Figure 4-19 shows the schematic of the box wiring.

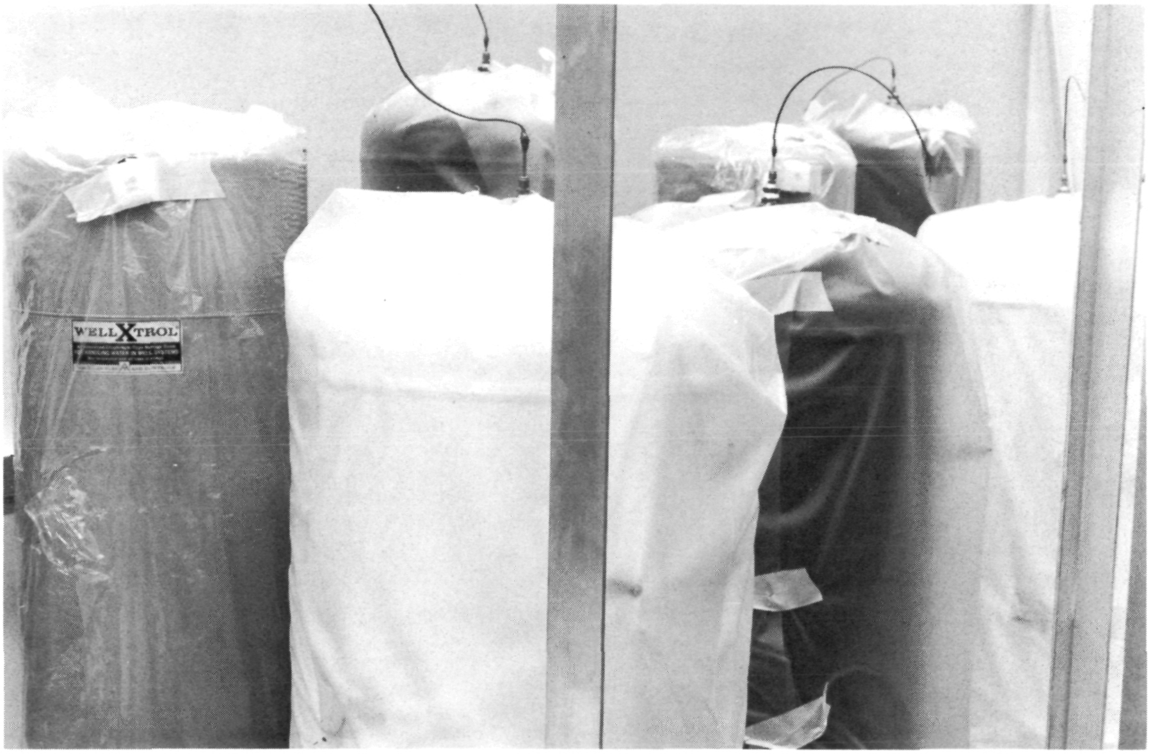

Figure 4-18. System Tankage Arrangement

4.4.2 Thrustor Module

The thrustor module layout design and fabrication was done in the identical manner as the storage and feed assembly skids. All components are mounted on a 0.6 m x 0.9 m (2 by 3 ft) panel with the interfacing wiring connector plugging into a small electrical box, also on the panel. Figure 4-20 shows the final module assembly.

4.5 SYSTEM TESTING AND OPERATION

As stated previously, each component was individually acceptance tested and the control console run through engineering checkout. Thus, system testing was limited to those aspects of system design and operation not tested at the component level. The resulting tests are summarized below and detailed in Table 4-6.

A. System Plumbing Proof and Leak

B. Wiring check from the skid interface box to individual components

C. Manual control from the console

D. Automatic system operation checkout

E. System acceptance test.

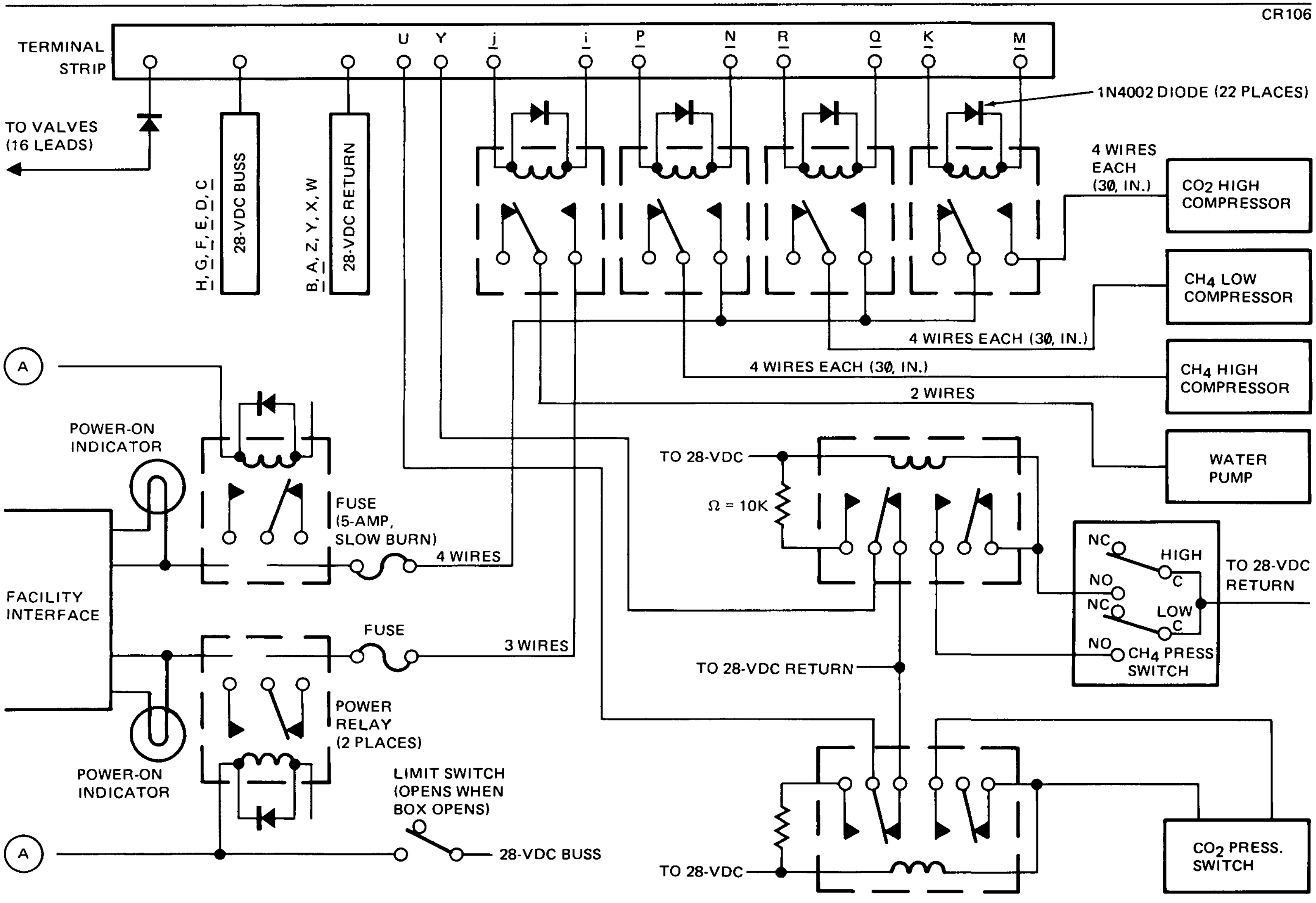

Figure 4-19. Storage/Feed Electrical Interface Schematic

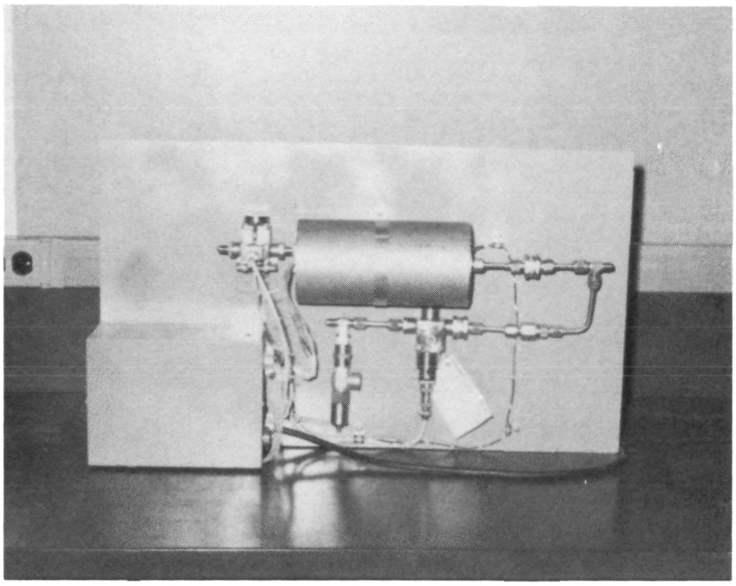

Figure 4-20. Thruster Module Assembly

All of the above were straightforward, but the acceptance test requires some additional explanation. This test is required to show total system operation in the automatic mode. This was done by programming a 700-sec program covering all phases of operation. The program used is shown in Tables 4-7. To aid in NASA installation and operation, and operations manual was prepared and included with the system delivery (Reference 15). Its principal contents were:

A. System/Facility Interface Requirements
B. System Setup
C. Event Detection Board Programming
D. Operational Characteristics
E. Component Description Sheets
F. Component Acceptance Test Data.

Table 4-6

RESISTOJET SYSTEM TEST PROGRAM

PHILOSOPHY:

- Checkout Tests at Logical Points
  - Circuit Boards
  - Control Console
  - Major Components
  - Skid Assembly
- Thorough Functional Checkout of Integrated System
- System Checkout and Acceptance Tests with GN_2
  - Leak Tight
  - Verify Manual and Automatic Operation
  - Verify Semiautomatic (Override)
  - Verify Advance Component Performance
- Testing Level
  - Available Components
    - Vendor - Normal, no Special Test Required
    - MDAC - Acceptance (Proof, Leakage, Func., Perf.)
  - Advance Components
    - Vendor - Demonstration, Acceptance
    - MDAC - Development, Acceptance
  - Electronic
    - MDAC - Checkout, Acceptance
  - System
    - MDAC - Checkout, Acceptance (Proof, Leak, Func.)

Table 4-7

SYSTEM ACCEPTANCE TEST SEQUENCER PROGRAM

Time	
10	Enable Start Sequence
20	Open Tank Isolation Valves (1, 2, 7, 8, 13, 14)
30	Open Reg. Isolation Valves, Pressure Valves, Fac. Valves (5, 6, 11, 12, 15, 16, 23-25)
40	Start Compressors
50	Enable Thrustor Sequences
60	Open Gas Module Valve (17)
70	Enable CH_4 Sequencer
80	Close CO_2 Flow Valves (9, 10); Open CH_4 Tank Valves (1, 2)
90	Open Gas Module Valve (17)
100	Close Water Module Valve (18)
110	Turn on Thrustor Heater No. 1
120	Open Thrustor Valve No. 1 (19)
130	Open CH_4 Flow Valves (3, 4)
140	
150	
160	Turn Off Thrustor Heater No. 1
170	Close Thrustor Valve No. 1 (19)
180	Turn on Thrustor Heater No. 2
190	Open Thrustor Valve No. 2 (20)
200	Enable CO_2 Sequencer
210	Close CH_4 Flow Valves (3, 4), Open CO_2 Tank Valves (7, 8)
220	Open Gas Module Valve (17)
230	Close Water Module Valve (18)
240	Open CO_2 Flow Control Valves (9, 10)
250	
260	
270	Turn Off Thruster Heater No. 2
280	Close Thrustor Valve No. 2 (20)
290	
300	Enable H_2O Start Sequence
310	Close CO_2 and CH_4 Flow Valves (3, 4, 9, 10); Open Water Valves (13, 14, 15, 16)

Table 4-7

SYSTEM ACCEPTANCE TEST SEQUENCER PROGRAM (Continued)

Time	
320	Close Gas Module Valve (17)
330	Turn on Vaporizer
430	Turn on Thruster Heater No. 3
440	Open Thrustor Valve No. 3 (21)
450	Open Water Module Valve (18)
460	
470	
480	
490	
500	Enable H_2O Stop Sequence
510	Close Water Tank Valves (13, 14)
520	
530	
540	Close Water Module Valve (18)
550	
560	
570	Turn Off Vaporizer
580	Turn Off Thrustor Heater No. 3
590	Close Thrustor Valve No. 3
600	Turn Off Compressors
610	Enable System Stop Sequence
620	Close Valves (3, 4, 9, 10, 23-25); Open Valves (13, 14)
630	Close Valves (5, 6, 11, 12)
640	Close Valves (1, 2, 7, 8, 15, 16)
650	Close Valves (17, 18)
660	
670	
680	
690	
700	

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5. Anon.: Development of a Biowaste Resistojet Propulsion System Propellant Management and Control Subsystem, Reliability and Quality Assurance Plan. McDonnell Douglas Astronautics Company.

6. Anon.: Development of a Water Vaporizer for Resistojet Applications. The Marquardt Company Report S-1244, November 1972.

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Appendix

RESISTOJET SYSTEM DEVELOPMENT— SYSTEM OPERATING LOGIC

A. 1 INTRODUCTION

The Space Station Biowaste Resistojet Propulsion system is required to operate automatically, with little or no crew participation except for maintenance/repair, etc. Thus, system control logic is required to acquire S/AC data, calculate impulse requirements, determine propellant utilization and provide the necessary operating commands; typically once per orbit. Furthermore, the interface with the ECLS system (propellant supply) and the hig h duty cycle and usage (25 to 80 percent each orbit) makes operational control significantly different and more complex than conventional systems. The detail procedures necessary for this operational logic and flow chart diagrams of system operation are provided in this bulletin. The format is such that computer programming can be accomplished using these diagrams and tables.

A. 2 SUMMARY

The overall operational functional flow diagram is shown in Figure A-1. Stabilization/Attitude Control (S/AC) data (CMG gimbal angles, orbit parameters) are determined and impulse requirements calculated. Propulsion system data is used in conjunction with the impulse requirements to select thrustor power level, and determine propellant utilization. Operating commands are then provided to system components and thrustors.

A. 3 SYSTEM OPERATION

The system operational control program can be divided into three major parts:

A. Thrustor Selection—Determine thrustor selection based on orientation, inhibits, and past usage.

B. Impulse Requirements Definition—Determine impulse requirements (impulse magnitude and direction) and propellant availability.

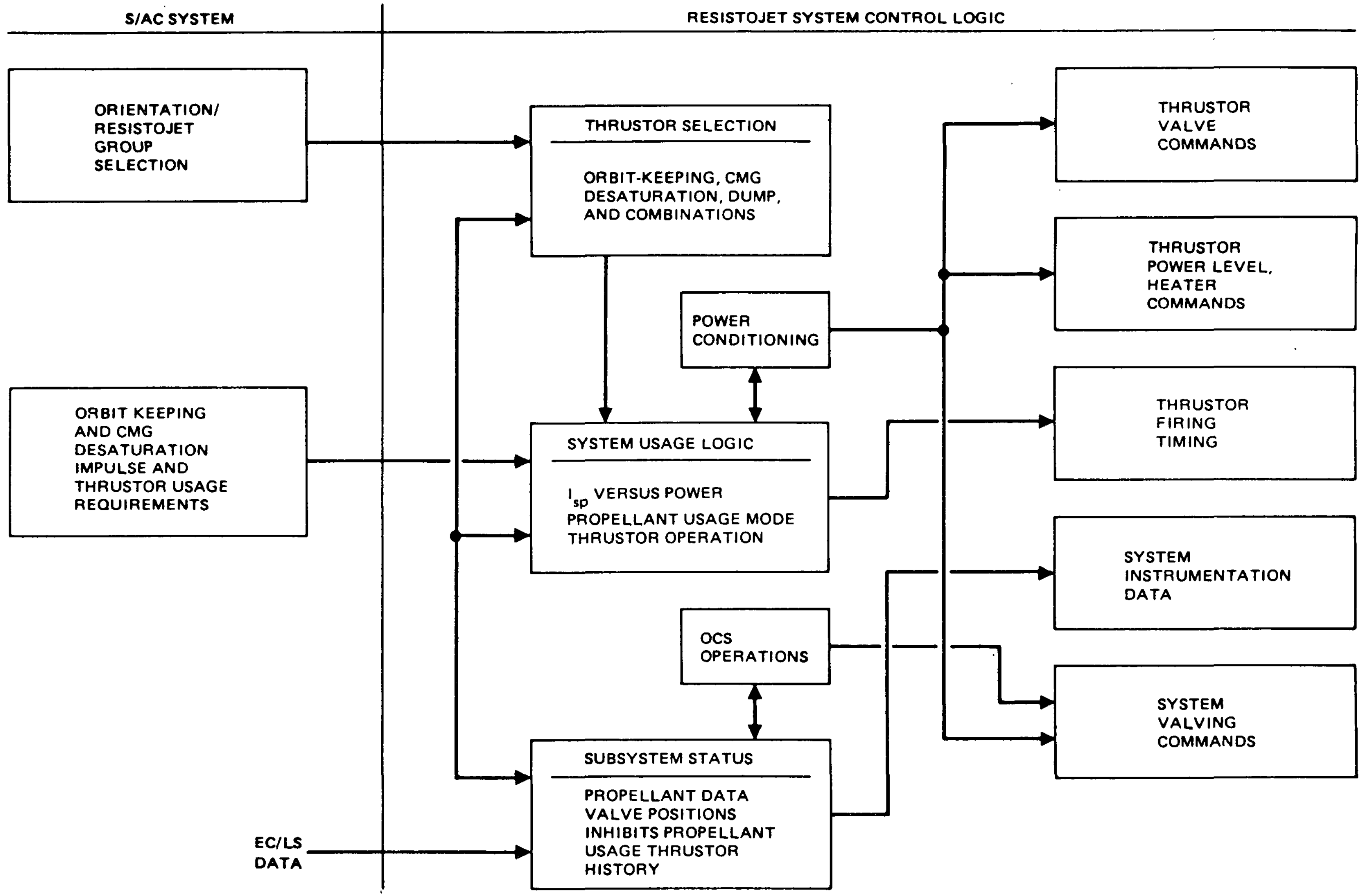


Figure A-1. Resistojet System Operation

C. System Operation—Determine propellant utilization, thrustor power level, and thrustor firing times based on impulse requirements and system status.

Figure A-2 shows the master system program, with the above three sections enclosed within the heavy boundaries. Details are explained in the following subsections:

A.3.1 Thrustor Selection

A manual operation, either by keyboard or a switch, selects the Space Station orientation on the panel which in turn gangs the correct thrustor valves (resistojets and monoprops) to a common bus for the orbit keeping function. This operation flags the orientation. For the horizontal or X-POP/OR orientation which aligns a particular body (or principal) axes to the velocity vector, a single gang of thrustors is connected to the orbit keeping bus. The thrustors aligned to the -X axis are ganged to the orbit keeping bus for the horizontal orientation while the thrustors aligned to the -Y axis for the X-POP/OR orientation. In the X-POP orientation, the Y and Z axes of the Space Station rotate with respect to the orbit velocity vector. For this orientation, four orbit keeping buses are used with the four thrust directions, +Y, -Y, +Z, and -Z. The activation of each bus is synchronized with the orbit timer for the correct thrustor firing angle.

The desaturation thrustors for the X-POP and X-POP/OR orientations are ganged to respective buses for the six moment directions. The number of thrustors for each desaturation operation is determined from a later test condition in the logic flow diagram. There are two sets of desaturation thrustors available for the horizontal orientation for which the selection will be determined from a later test condition in the logic flow diagram.

Vehicle thrustor arrangement provides at least two (and usually more) different potential thrustor combinations for each operating mode and each orientation. The subsystem logic will determine thrustor selections based on orientation, but additional logic is required to select the actual thrustors to use (i.e., if a thrustor or thrustor module is inhibited ((malfunctioning heater, valve, isolation valve closed, etc.)), then that unit cannot be used). Therefore,

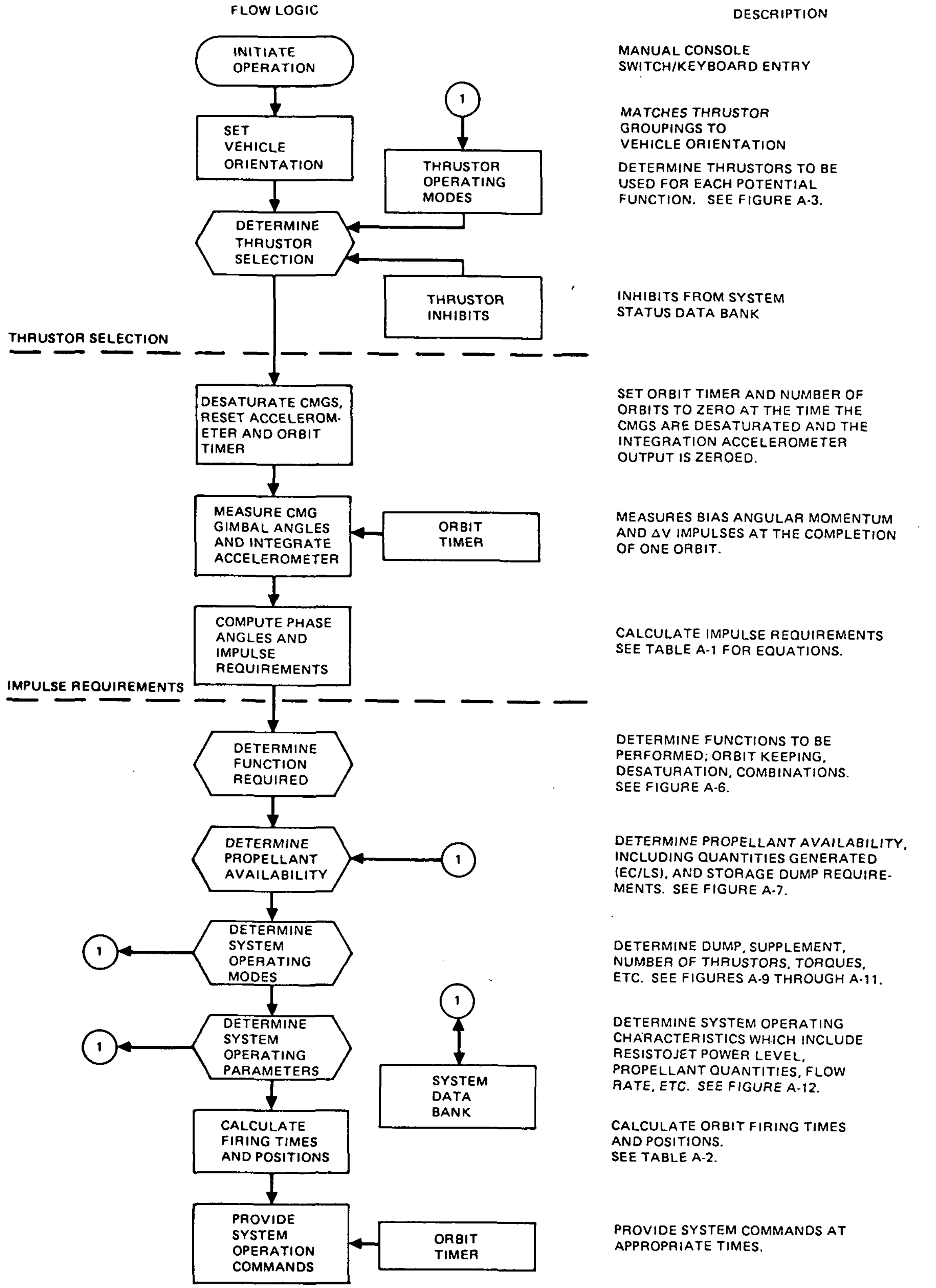


Figure A-2. Resistojet System Operational Logic

one primary and two secondary (backup) sets of thrustors will be determined for each operating mode (orbit-keep, dump, etc.). A block schematic of this selection process is shown in Figure A-3, and is done for each potential operating mode listed below.

Orbit-keeping

±P, Y, R desaturation

Orbit-keeping plus ±P, Y desaturation combined

Orbit-keeping plus ±Y desaturation combined

Orbit-keeping plus ±P desaturation combined

Dump

The matrix showing thrustor primary and secondary pairings for each mode is shown in Figures A-4 and A-5.

A. 3. 2 Impulse Requirements Definition

After the orientation has been flagged and thrustors selected, the CMG gimbal angles are commanded to a zero position of the X, Y and Z axis angular momentum components and the high thrust firing time accumulators are reset to zero. Upon reaching the zeroed position, the output of the integrating accelerometers is set to zero and the orbit timer is reset and activated. This operation zeros the drag impulse and the CMG desaturation impulse at the start of one orbit. A test is then used to determine the completion of one orbit. This is obtained from the orbit timer that is set from the navigation data. At the completion of one orbit, the gimbal angles of the firing time accumulators are measured to determine the bias angular momentum components ($h_X (T_o)$, $h_Y (T_o)$, $h_Z (T_o)$). The high-thrust firing time accumulators must be monitored in case the CMG capacity is exceeded before the completion of one orbit. The integrated output of the accelerometer ($\Delta V(T_o)$) is measured to determine the orbit-keeping impulse. At the completion of the orbit, the parameter orbit is set set equal to its initial value (zero) plus one. This parameter is used in a later test condition.

The impulse requirements (orbit-keeping and desaturation) are computed each orbit from these measurements. The impulse calculations are shown in Table A-1. The difference in the impulse calculations between the first orbit

FLOW LOGIC

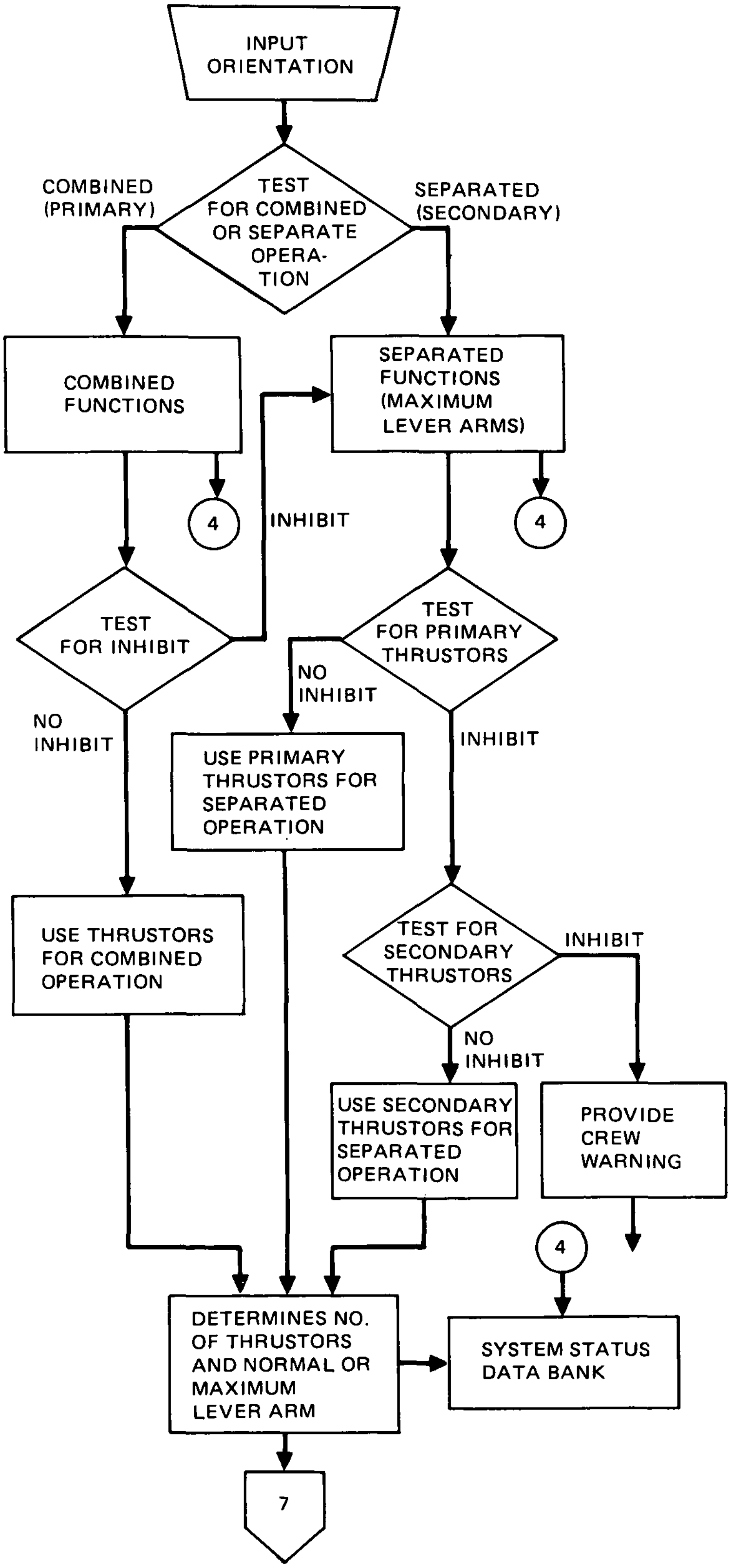


Figure A-3. Thrustor Select Logic

DESCRIPTION

THRUSTOR SELECTION IS REQUIRED FOR THE FOLLOWING FUNCTIONS:

ORBIT KEEP
±P, Y, R DESATURATION
COMBINED ORBIT KEEPING AND DESAT. DUMP.

DUMP SYSTEM IS OPERATED WITH FUNCTIONS COMBINED UNLESS OTHERWISE SPECIFIED.

THE SEPARATED FUNCTIONS UTILIZE THE MAXIMUM LEVER ARMS

DETERMINES THRUSTOR GROUPS FROM S/AC SELECT MATRIX. SEE FIGURES A-4 AND A-5.

THRUSTOR SELECTIONS STORED IN DATA BANK SYSTEM

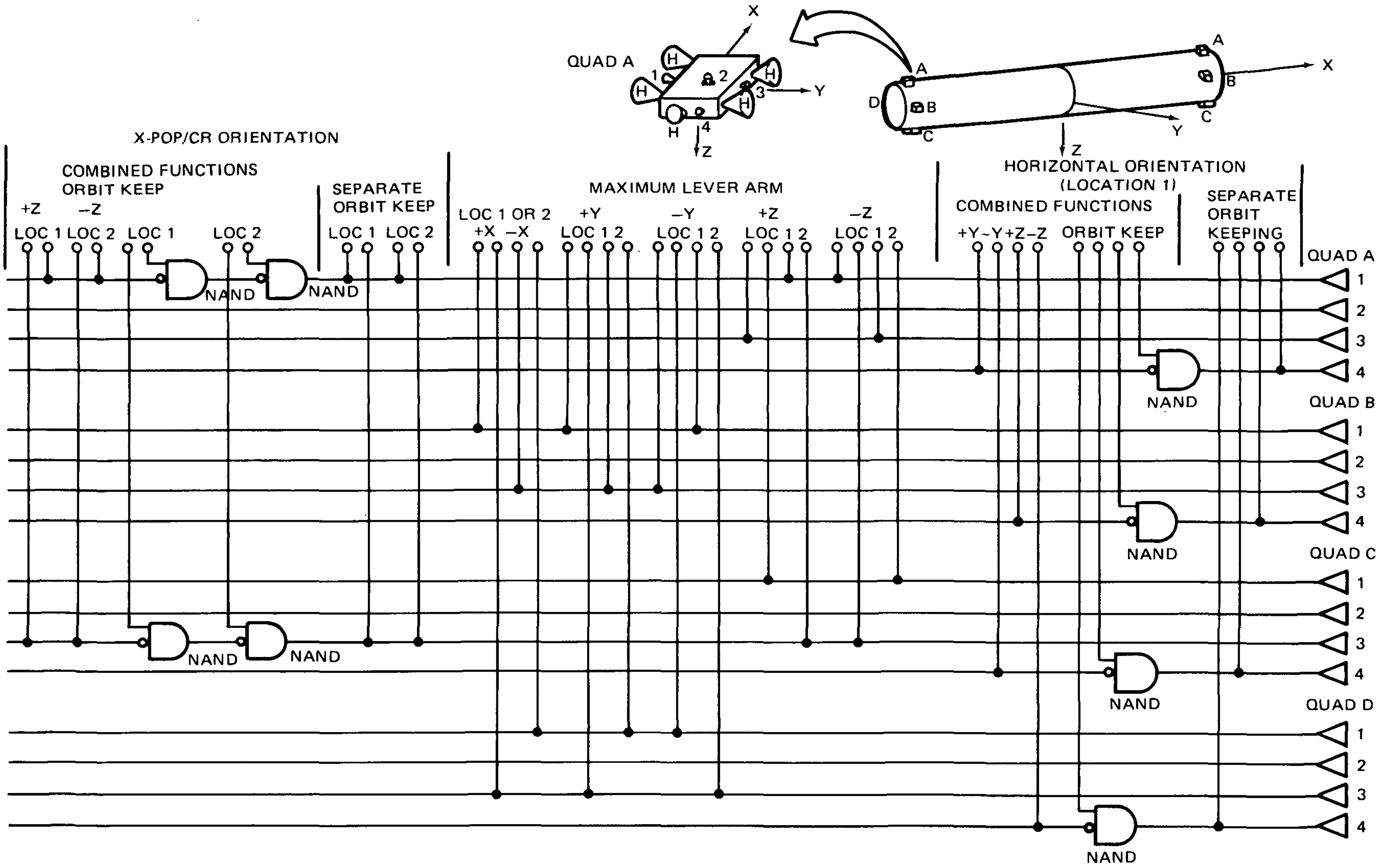


Figure A-4. Thrustor Select Logic

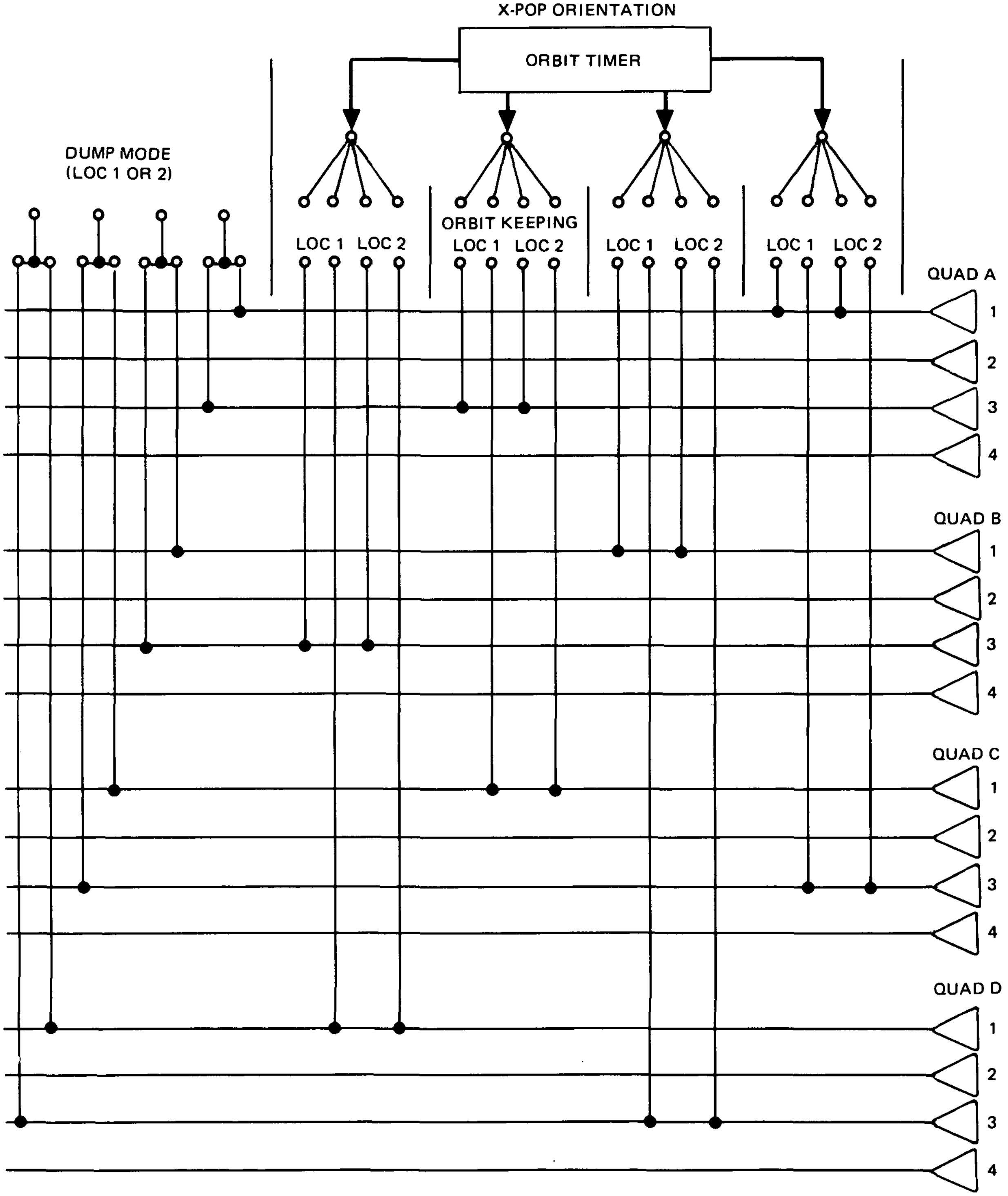


Figure A-5. Thrustor Select Logic

Table A-1

PHASE ANGLE AND IMPULSE CALCULATION

Computation	Orientation: Horizontal	X-POP/OR	X-POP
Efficiency Factor	(1) $eff = \frac{1}{(\phi_f/2)} \int_0^{\phi_f/2} \cos \phi_f \, d\phi_f \quad \frac{\sin(\phi_f/2)}{(\phi_f/2)}$ (Used for desaturation)	Same as Eq. (1) (Used for desaturation)	Same as Eq. (1) (Used for Orbiting-Keeping)
Desaturation Impulse (lb-ft-sec) A. Impulse computed at the end of first orbit B. Impulse computed at the end of second or more orbits	(2a) $h_{desat} = \frac{1}{eff}\left[h_X^2(T_o) + h_Z^2(T_o)\right]^{1/2} + h_Y(T_o)$ (2b) $h_{desat} = \frac{1}{eff}\left[h_X^2(NT_o) + h_Z^2(NT_o)\right]^{1/2} + h_Y(NT_o) - \left[N_1 TL \frac{1}{eff} \psi_{fs}(N) \frac{1}{2} + N_1 TL\theta_{fs}(N) \frac{1}{2}\right] \frac{T_o}{2\pi}$ where N (number of orbits) > 2	(5a) $h_{desat} = h_X(T_o) + \frac{1}{eff}\left[h_Y^2(T_o) + h_Z^2(T_o)\right]^{1/2}$ (5b) $h_{desat} = h_X(NT_o) + \frac{1}{eff}\left[h_Y^2(NT_o) + h_Z^2(NT_o)\right]^{1/2} - \left[N_1 TL_X \phi_{fs}(N) \frac{1}{2} + N_1 TL\theta_{fs}(N) \frac{1}{2}\right] \frac{T_o}{2\pi}$	(7a) $h_{desat} = h_X(T_o) + h_Y(T_o) + h_Z(T_o)$ (7b) $h_{desat} = h_X(NT_o) + h_Y(NT_o) + h_Z(NT_o) - \left[N_1 TL\,(\psi_{fz}(N)) \frac{1}{2} + N_1 TL_X \phi_{fs}(N) \frac{1}{2}\right] \cdot \frac{T_o}{2\pi}$
Phase Angle (deg)	(3) $\phi_o = \tan^{-1} \frac{h_X(T_o)}{h_Z(T_o)}$	(6) $\phi_o = \tan^{-1} \frac{h_Y(T_o)}{h_Z(T_o)}$	No Phase Angle required
Orbit-Keeping Impulse (lb-sec)	(4a) $\Delta P_{com} = M_S \, \Delta V$ (4b) $\Delta P_{com} = M_S \, \Delta V - N_2 T \, \phi_{fd}(N) \frac{T_o}{4\pi}$	Same as Eq. (4a) and (4b)	(8a) $\Delta P_{com} = \frac{1}{eff} M_S \, \Delta V$ (8b) $\Delta P_{com} = \frac{1}{eff} \left[M_S \, \Delta V - N_2 T \, \psi_{fd}(N) \frac{T_o}{4\pi}\right]$

$h_X(T_o)$, $h_Y(T_o)$, $h_Z(T_o)$ Roll, Pitch, and Yaw measured angular momentum components

ϕ_f = Firing angle
h_{desat} = Computed desaturated impulse
N_1 = Number of thrustors for desaturation
T = Thrust level
L_X = Roll lever arm
ϕ_o = Phase angle

M_S = Mass of Space Station
L = Pitch or yaw lever arm
T_o = Orbit period
$\phi_{fd}(N)$ = Orbit-keeping firing angle
$\phi_{fs}(N)$, $\theta_{fs}(N)$, $\psi_{fs}(N)$ = Roll, pitch, and yaw firing angles

N_2 = Number of thrustors for orbit-keeping
V = Integrated output of the accelerometer
P_{comm} = Computed orbit-keeping impulse
N = Number of orbits

and succeeding orbits is that during the first orbit the impulse measurement do not have to compensate for apost-thrustor firing as required for the second or succeeding impulse measurements

A.3.3 System Operation

A.3.3.1 Function Determination

After the separate impulse requirements are calculated, the propulsive functions, propellant availability and operating modes and parameters are determined.

The logic for the Thrustor Operating Mode is shown in Figure A-6 and is explained as follows: A test condition for the first orbit is made. At the end of the first orbit the impulse requirements for the next orbit are twice that computed. This takes care of the impulse accumulated on the first orbit and the impulse to be accumulated for the next orbit. If it is not the first orbit, then the impulse requirements for the present orbit are equal to that compared.

At this point, the results of the thrustor select are used to determine if the orbit-keeping functions are to be combined or separate, and the total impulse requirements computed.

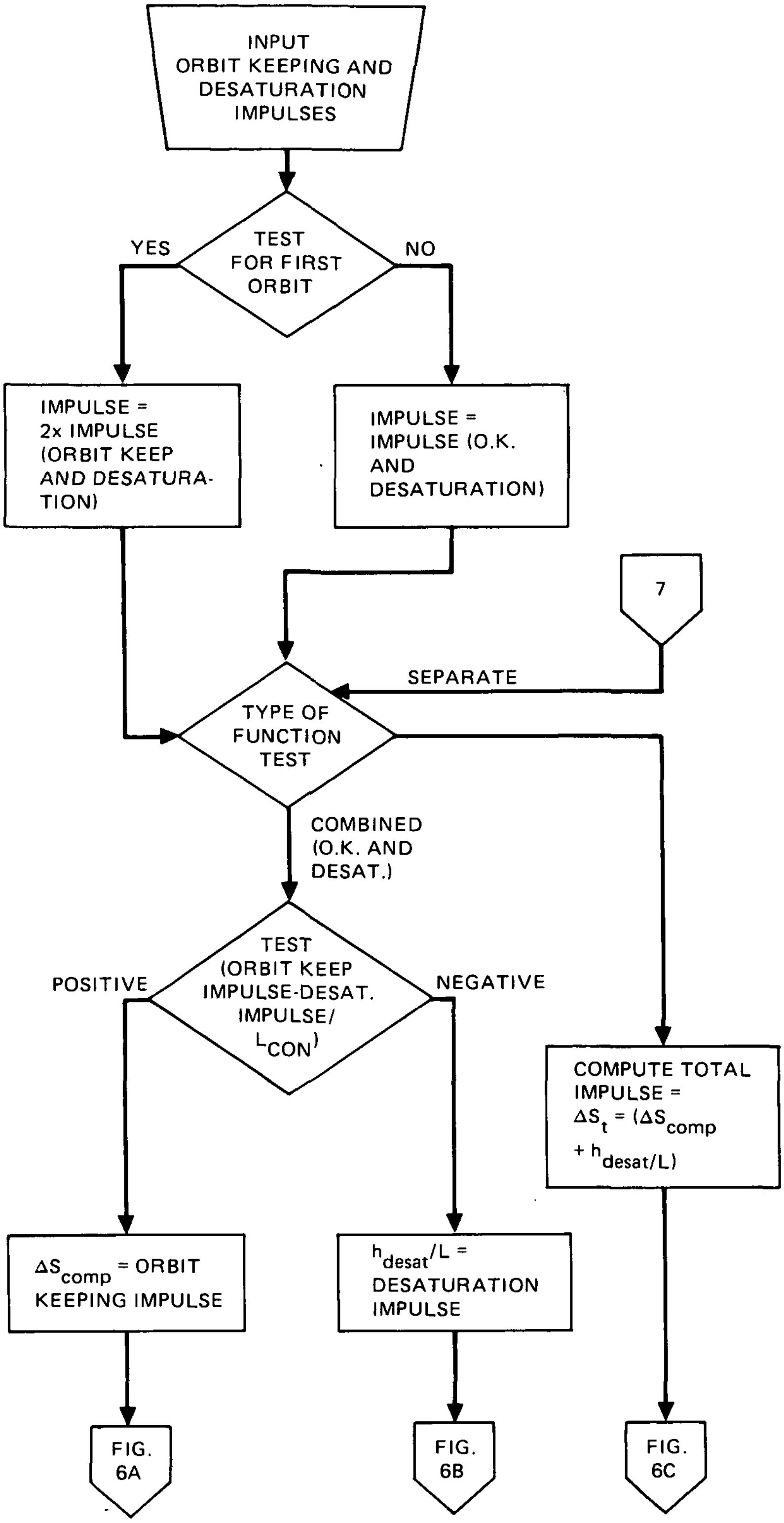
A.3.3.2 Gas Propellant Availability

The available biowaste propellant is determined from ECLS-generated gases and current storage quantities. A logic diagram of the propellant determination scheme is shown in Figure A-7. This procedure will determine the amount of propellant available for impulse requirements and it will also define any propellant dumping or storage required to maintain desired tank pressure.

The first step is to determine if the propellant to be generated during the firing period is sufficient to meet impulse requirements of if the tank pressure is greater than operating pressure (nominally 250 to 300 psia). Figure A-7, shows the calculations required to determine propellant and impulse availability, and is done for both CO_2 and CH_4. If the impulse required is less

FLOW LOGIC

DESCRIPTION

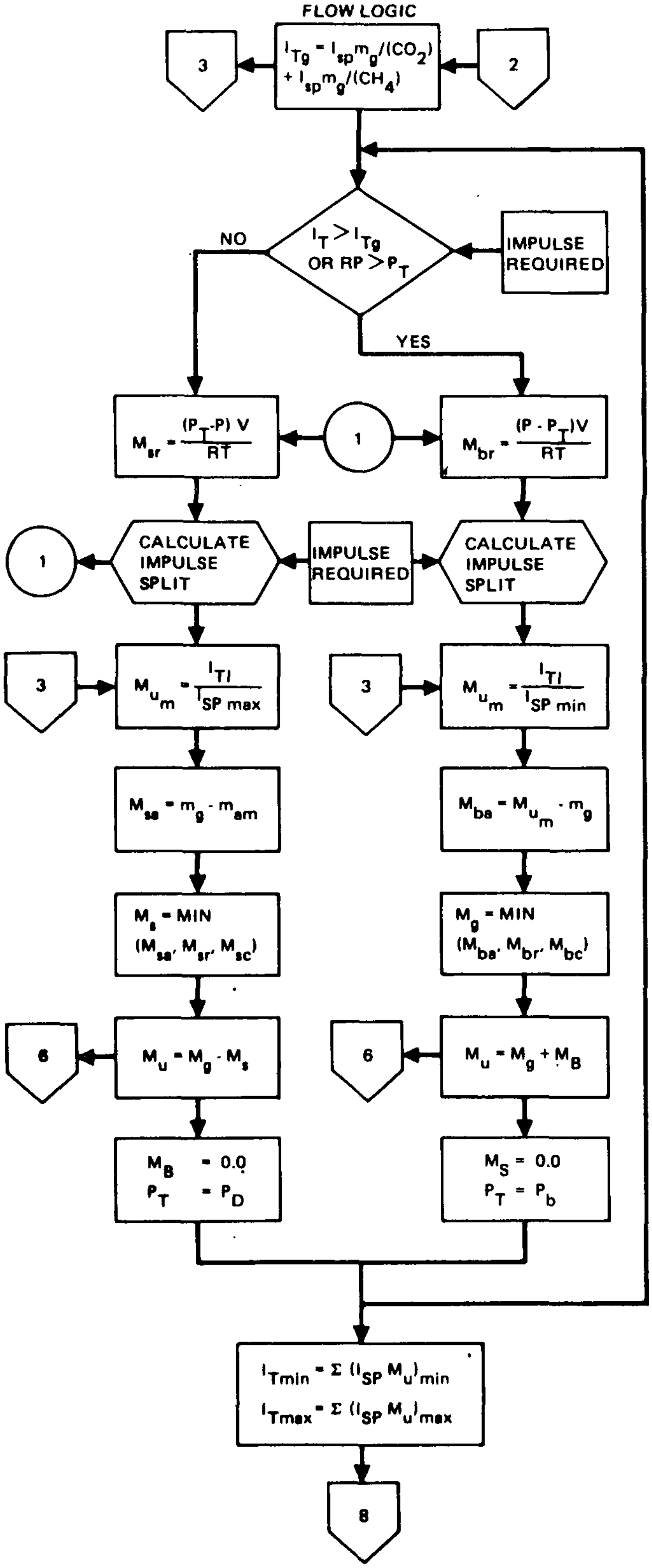


IF FIRST ORBIT, NEED IMPULSE FOR FIRST AS WELL AS SECOND ORBIT. AFTER THAT, ONLY NEED IMPULSE FOR COMING ORBIT.

CHOOSE FUNCTION USING RESULTS OF THRUSTOR SELECT LOGIC (FIGURE A-3).

IDENTIFIES WHICH IMPULSE TO BE USED FOR THE I_{SP} AND CONTROL LEVER ARM SELECTION.

Figure A-6. System Functions



DESCRIPTION

CALCULATE THE MAXIMUM IMPULSE AVAILABLE FROM PROPELLANT GENERATED. I_{SP} USED IS MAXIMUM DESIRED I_{SP}.

DETERMINE WHETHER TO CONSIDER STORAGE OR BLOWDOWN.

CALCULATE MASS REQUIRED TO CHANGE PRESSURE TO P_T PSIA.

DETERMINE THE TOTAL IMPULSE SPLIT BETWEEN CO_2 AND CH_4. SEE FIGURE A-8.

CALCULATE THE LIMITING AMOUNT OF PROPELLANT REQUIRED TO PROVIDE THE NECESSARY IMPULSE, BASED ON DESIRED LIMITING I_{SP}.

I_{TI} = IMPULSE ALLOCATION FOR EACH PROPELLANT

TOTAL PROPELLANT AVAILABLE IS DIFFERENCE BETWEEN THAT GENERATED AND THAT REQUIRED FOR IMPULSE.

STORAGE OR BLOWDOWN QUANTITY IS MINIMUM OF REQUIRED, AVAILABLE, AND MANUAL SET OPTION.

NET QUANTITY AVAILABLE IS THAT GENERATED, ALTERED BY CHANGES, IF ANY.

SET NON-APPLICABLE CHANGE TO 0.0 AND RESET TEST PRESSURE (WILL NOT CHANGE UNTIL LIMIT REACHED).

CALCULATE TOTAL MINIMUM AND MAXIMUM IMPULSE AVAILABILITY, BASED ON DESIRED LIMITS OF I_{SP}.

NOTE:

MINIMUM AND MAXIMUM I_{SP} ARE THOSE DESIRED, NOT NECESSARILY THRUSTOR LIMITS. THEY ARE AN INPUT QUANTITY, AND CAN BE CHANGED AS DESIRED.

Figure A-7. Propellant Availability

than the maximum available and tank pressure less than operating pressure, the procedure is as follows for storage:

A. Calculate storage make-up requirement

$$m_{SR} = \frac{(P_T - P)\,V}{RT}$$

B. Calculate impulse split between CO_2 and CH_4 (see Figure A-8 and Section A. 4).

C. Calculate minimum propellant required to meet impulse requirements

$$m_{u_m} = \frac{I_{Ti}}{I_{SP_{max}}}$$

D. Calculate propellant available for storage.

$$m_{sa} = m_g - m_{u_m}$$

E. Determine actual mass to be stored.

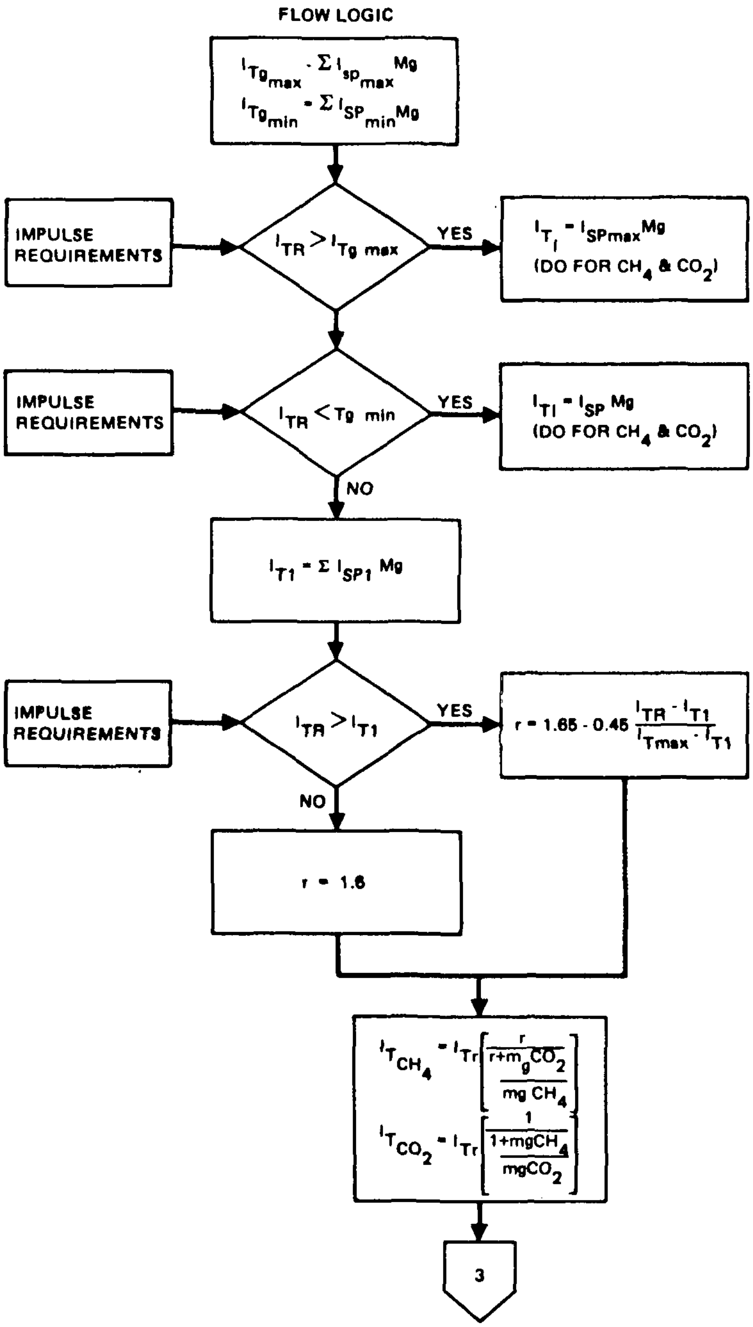
$$m_s = \text{minimum}\,(m_{sa},\ m_{sr},\ m_{sc})$$

$$m_{sc} = \text{preset maximum to be stored during any firing period}$$

F. Calculate propellant to be used during the next firing period.

$$m_u = m_g - m_s$$

A similar procedure is utilized if additional propellant is required ($I_T > I_{T_{Avail}}$) or desired ($P > P_T$). Finally, minimum and maximum total impule ($I_{CH_4} + I_{CO_2}$) availability is calculated.



DESCRIPTION

CALCULATE MAXIMUM AND MINIMUM IMPULSE AVAILABLE FROM GENERATED PROPELLANT. TOTAL EQUALS SUM OF CO_2 AND CH_4.

TEST IF IMPULSE REQUIRED IS GREATER THAN MAXIMUM GENERATED. IF SO, IMPULSE IS CALCULATED AS MAXIMUM.

IF ABOVE TEST FAILS, TEST IF IMPULSE REQUIRED IS LESS THAN MINIMUM GENERATED. IF SO, IMPULSE IS CALCULATED AS MINIMUM.

IF ABOVE TEST FAILS, CALCULATE IMPULSE GENERATED BASED ON A 1000oK CHAMBER TEMPERATURE. THIS IS THE CH_4 LIMIT.

TEST IF IMPULSE IS GREATER THAN THAT AVAILABLE AT 1000oR. IF SO, IMPULSE IS SPLIT TO ASSURE CH_4 LIMIT NOT EXCEEDED.

IF ABOVE TEST FAILS, THE RATIO IS 1.6, THE RATIO OF EQUAL USAGE.

CALCULATE THE IMPULSE SPLIT BETWEEN CH_4 AND CO_2.

Figure A-8. Impulse Split

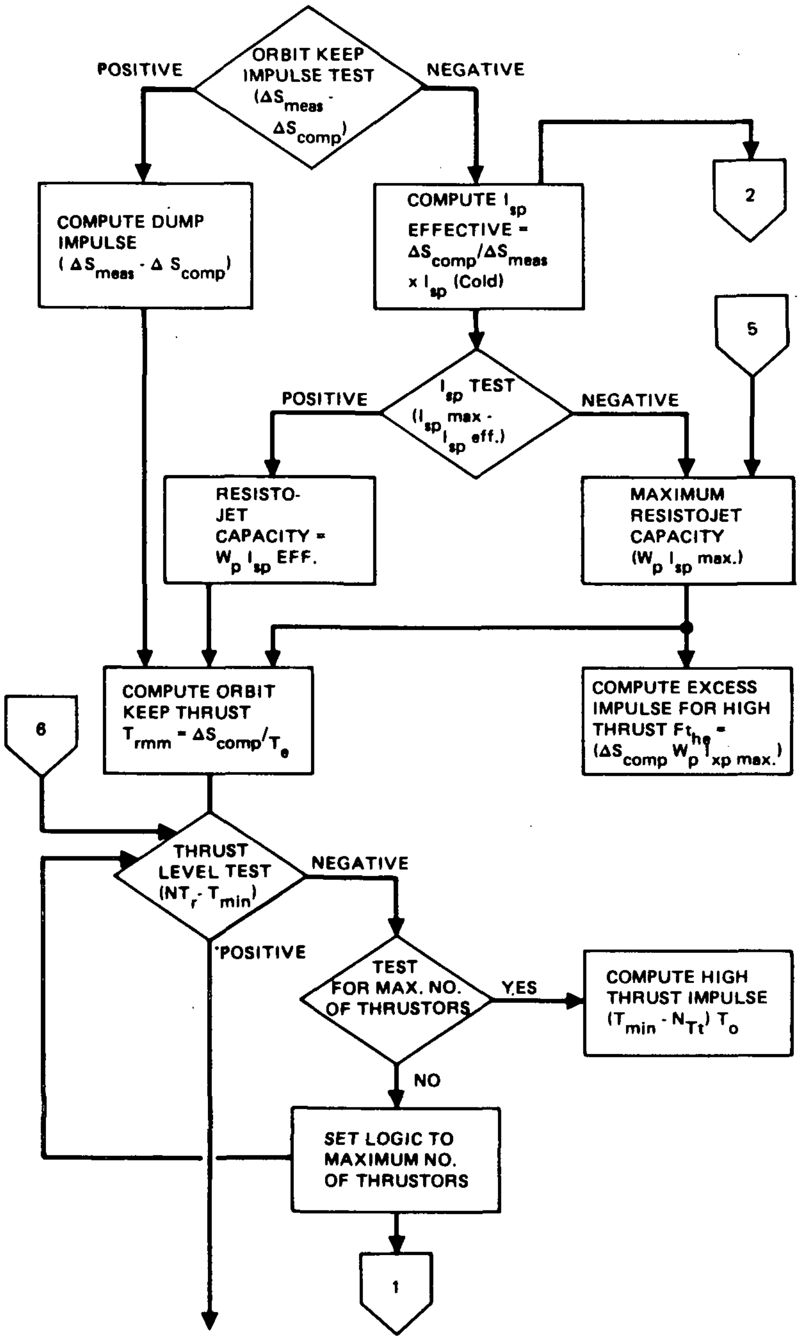
A.3.3.3 System Operating Modes

The results of function determination and propellant availability are combined to determine the system operating mode. First is a test to determine which impulse is the larger, the orbit-keeping or the desaturation impulse. The orientation is flagged so that the correct control lever arm is used. If functions are combined, the larger of these computed impulses will be used in a test with the measured resistojet impulse capacity. Going through this loop of the logic flow the computed orbit-keeping impulse is compared with the previously calculated resistojet impulse capacity. This test will determine the I_{sp} required for the resistojets and the additional high thrust impulse (if necessary). Figures A-9 through A-11 show the logic flow diagrams to determine the propellant I_{sp} and the supplement or dump mode requirements for the three test conditions of orbit-keeping impulse, desaturation impulse, and orbit-keeping plus desaturation impulse. The measured resistojet impulse (ΔS_{meas}) is less than the computed impulse (ΔS_{comp}) the I_{sp} is increased by the ratio ($\Delta S_{comp}/\Delta S_{meas}$) $I_{sp\ cold}$ up to the limit of $I_{sp\ max}$.

An electrical signal proportional to the effective I_{sp} new is used by the resistojet control electronics to determine the desired I_{sp}. Another test is now made to determine if the $I_{sp\ new}$ is greater than the maximum effective I_{sp} (including that provided by water supplement). If it is, then the excess (greater than the resistojet limit) impulse capacity is provided by the high thrust system. This excess capacity (Ft_{he}) is that defined within the block as (ΔS_{comp} - W_p ($I_{sp\ max}$)).

The results of the I_{sp} test also defines the resistojet impulse. Dividing this impulse by the orbit period (T_o) produces the minimum thrust level ($T_{\Omega\ min}$) for the resistojets. A thrust-level test is made to determine if the resistojet system has the thrust capacity. If not, a test is made to determine if the maximum number of thrustors are utilized. From the results of this test the maximum number of thrustors available for the orbit-keeping operation are selected and if this thrust level is still not sufficient the high thrust system is used to supplement this function. With the output of this last test the orbit-keeping impulse for the resistojets is computed.

FLOW LOGIC



DESCRIPTION

CALCULATE DUMP IMPULSE IF REQUIRED.

$$I_{sp_{cold}} = \frac{I_{sp_{min}}(CO_2)\,Mu_{CO_2} + I_{sp_{min}}(CH_4)\,Mu_{CH_4}}{Mu_{CO_2} + Mu_{CH_4}}$$

I_{sp} TEST TO DETERMINE IF SUPPLEMENT HIGH THRUST PROPELLANT IS REQUIRED.

$$I_{sp_{max}} = [I_{sp_{max}}(CO_2)\,M_{u_{CO_2}} + I_{sp_{max}}(CH_4)\,M_{u_{CH_4}} + I_{sp_{H_2O}}\,M_{uH_2O}]\,\frac{1}{(\Sigma Mu)}$$

DETERMINE HIGH THRUST IMPULSE IF REQUIRED.

RESISTOJET THRUST LEVEL TEST (CAN RESISTOJETS MEET TORQUE REQUIREMENTS?

CALCULATE HIGH THRUST FIRING TIMES AND POSITIONS. SEE TABLE A-3.

CALCULATE ORBIT FIRING TIMES AND POSITIONS FOR RESISTOJET. SEE TABLE A-2.

Figure A-9. Propellant I_{SP}

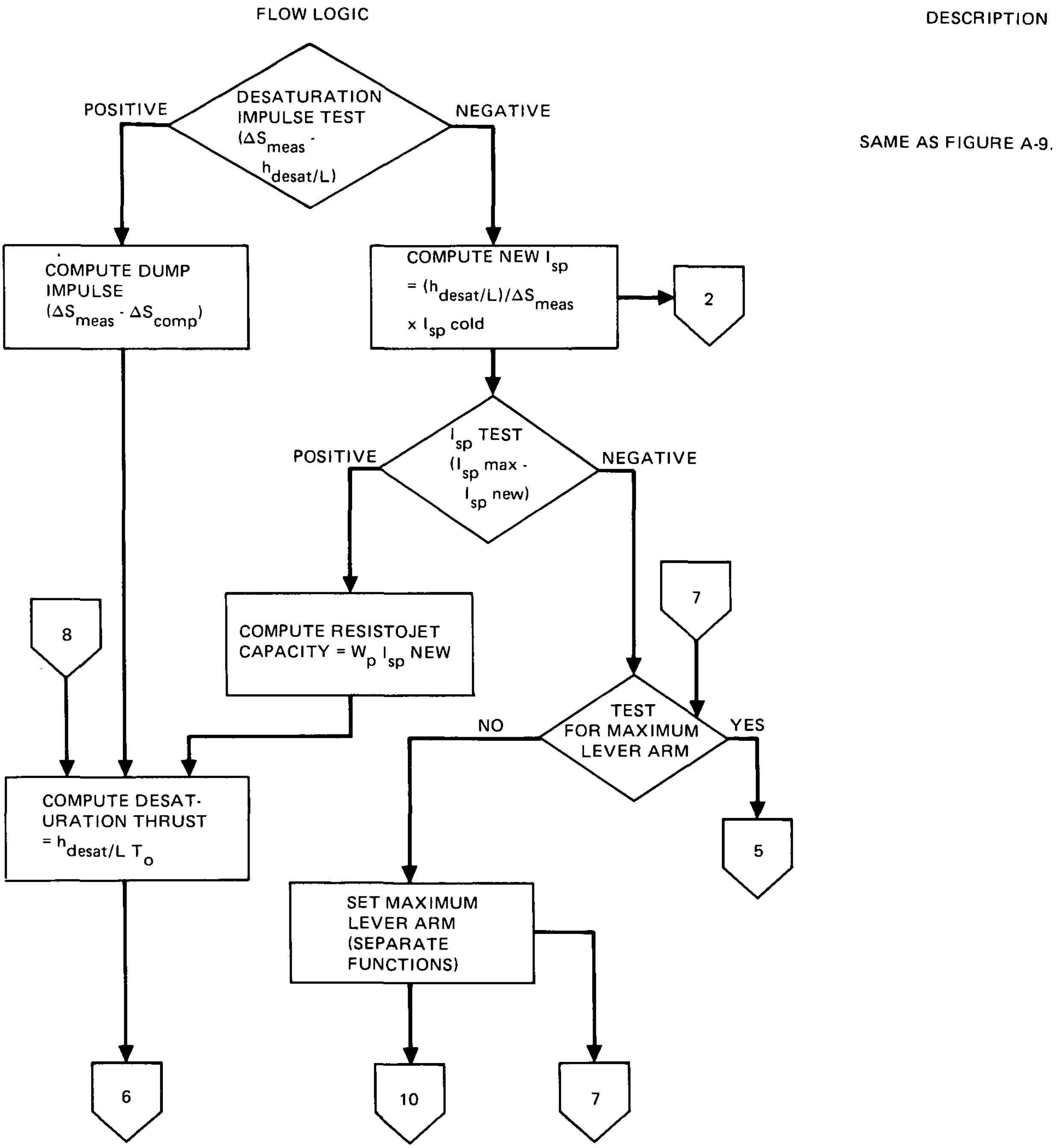
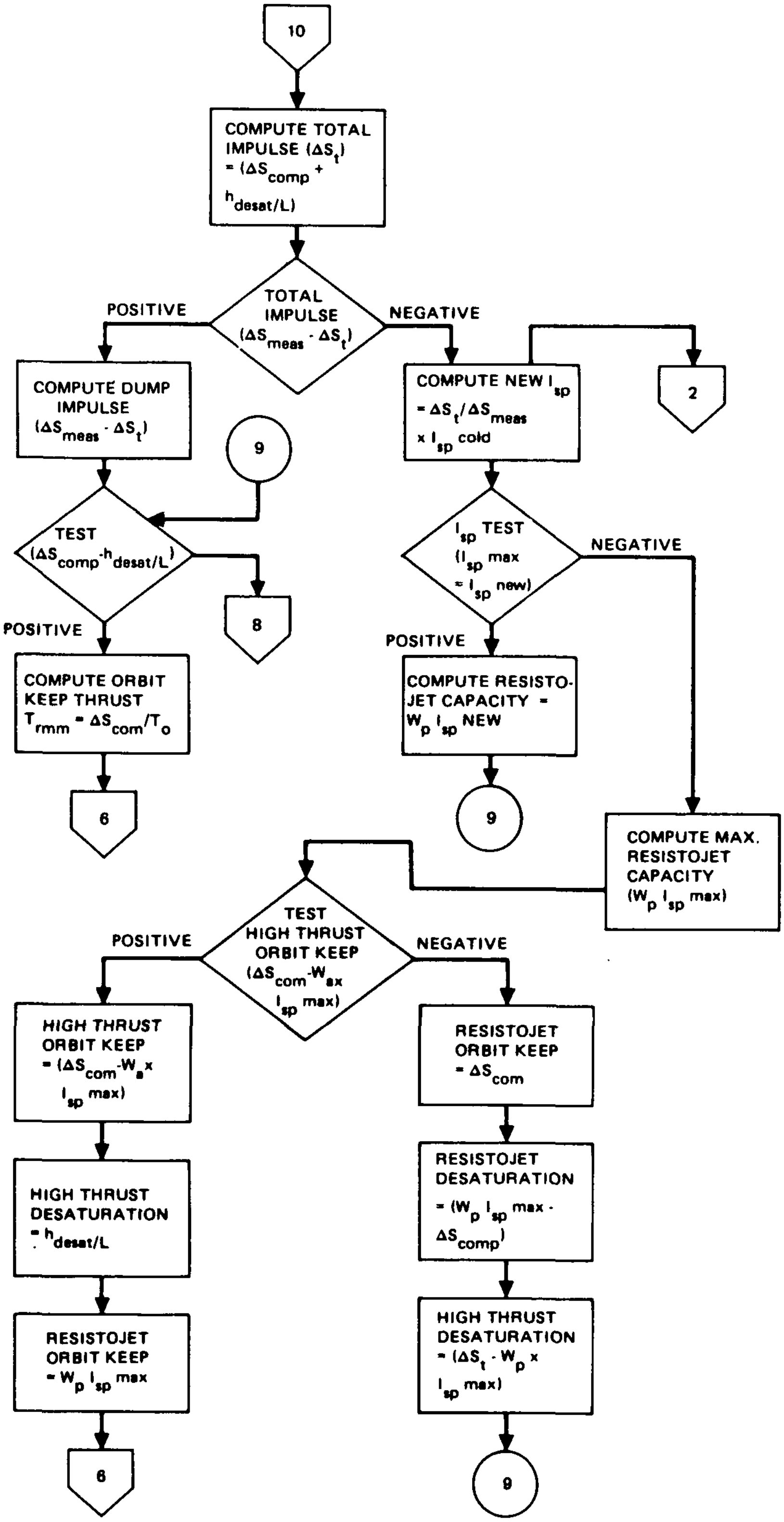


Figure A-10. System Impulse Requirements for Combined, Desaturation Mode



DESCRIPTION

SAME AS FIGURE A-9.

Figure A-11 System Impulse Requirements for Separate Mode

Going back to the test of the orbit-keeping impulse and the desaturation impulse, if the result from this test is negative (desaturation larger than orbit keeping) the measured resistojet impulse must be compared with the desaturation impulse. The desaturation impulse test will go through the same logic as the I_{sp} test for the orbit-keeping impulse. After the I_{sp} test there is one more test than that for the orbit-keeping impulse which is the test for the maximum lever arm. This test is only necessary for the horizontal orientation since two choices of thrustor lever arms for the pitch and yaw axes are available. Unless the desaturation impulse is very large the smaller lever arm for the pitch and yaw axes is desirable since an orbit-keeping impulse can be obtained from the desaturation operation.

The remainder of the logic flow for the desaturation impulse is the same as that for the orbit-keeping impulse up to the resistojet impulse computation.

The logic flow for the total impulse, desaturation and orbit keeping shown in Figure A-11 is similar to those given in Figures A-9 and A-10 except an additional test is required. This test is to determine which impulse, desaturation, or orbit-keeping, is the larger to perform the thrust level test.

A.3.3.4 System Operating Parameters

The system parameters are determined from propellant availability and operating mode. If impulse required is less than the minimum available, the minimum power level will be used. If the impulse required is greater than that available from the CO_2 and CH_4 gases, the quantity of water supplement (up to a maximum allowable) is determined. If the impulse is between these extremes, the appropriate power level (function of impulse, thrustor efficiency, etc.) is determined. Specific thrustor characteristics are shown, rates, durations, etc., are calculated.

A.3.3.5 Firing Data and Commands

After the impulse requirements for the resistojets have been computed, the orbital firing position and thrustor firing times are computed for the orbit keeping and CMG desaturation functions. These firing angle computations are shown in Table A-2. The computation of these thrustor firing times are

Table A-2

FIRING ANGLE CALCULATION

Firing Angle	Orientation: Horizontal	Orientation: X-POP/OR	Orientation: X-POP
Desaturation Firing Angle (2/Orbit)			
Roll Axis	No Requirement	(12) $\phi_{fs} = \frac{1}{2} \frac{h_{X\Omega}(T_o)}{(N_1 T) L_x} \times \frac{2\pi}{T_o}$	(15) $\phi_{fs} = \frac{\pi}{2T_o} \frac{h_{X\Omega}(T_o)}{(N_1 T) L_x}$
Yaw Axis	(9) $\Psi_{fs} = \frac{1}{2} \left[\frac{h^2_{X\Omega}(T_o) + h^2_{Z\Omega}(T_o)}{(N_1 T) L}\right]^{1/2} \times \frac{2\pi}{T_o}$	(13) $\Psi_{fs} = \frac{1}{2} \left[\frac{h^2_{Y\Omega}(T_o) + h^2_{Z\Omega}(T_o)}{(N_1 T) L}\right]^{1/2} \times \frac{2\pi}{T_o}$	(16) $\Psi_{fs} = \frac{\pi}{2T_o} \frac{h_{Y\Omega}(T_o)}{(N_1 T) L}$
Pitch Axis	(10) $\theta_{fs} = \frac{1}{2} \frac{h_{Y\Omega}(T_o)}{(N_1 T) L} \times \frac{2\pi}{T_o}$	No Requirement	(17) $\theta_{fs} = \frac{\pi}{2T_o} \frac{h_{Z\Omega}(T_o)}{(N_1 T) L}$
Orbit-Keeping Firing Angle (2/Orbit)	$(11)_1$ $\phi_{fd} = \left[\frac{\pi}{T_o} \frac{\Delta P_\Omega}{N_2 T} - \left(\frac{h_{Y\Omega}(T_o)}{(N_1 T) L} + \left\{\frac{h^2_{X\Omega}(T_o) + h^2_{Z\Omega}(T_o)}{(N_1 T) L}\right\}^{1/2}\right)\right]$	$(14)_1$ $\phi_{fd} = \frac{\pi}{T_o} \frac{\Delta P_\Omega}{N_2 T} - h_Y^2 (T_o \quad \frac{h^2_{Y\Omega}(T_o) + h^2_{Z\Omega}(T_o)}{(N_1 T) L}^{1/2}$	(18) $\phi_{fd} = 2 \text{ arc sin} \left[\frac{\pi}{4T_o} \left\{\frac{\Delta P_\Omega}{N_2 T} - \frac{h_{Y\Omega}(T_o) + h_{Z\Omega}(T_o)}{(N_1 T) L}\right\}\right]$

$h_{X\Omega}(T_o)$, $h_{Y\Omega}(T_o)$, $h_{Z\Omega}(T_o)$ - Roll, pitch, yaw resistojet angular momentum requirements

N_1 = Number of thrustors for desaturation

T = Thrust level

L_x = Roll lever arm

L = Pitch or yaw lever arm

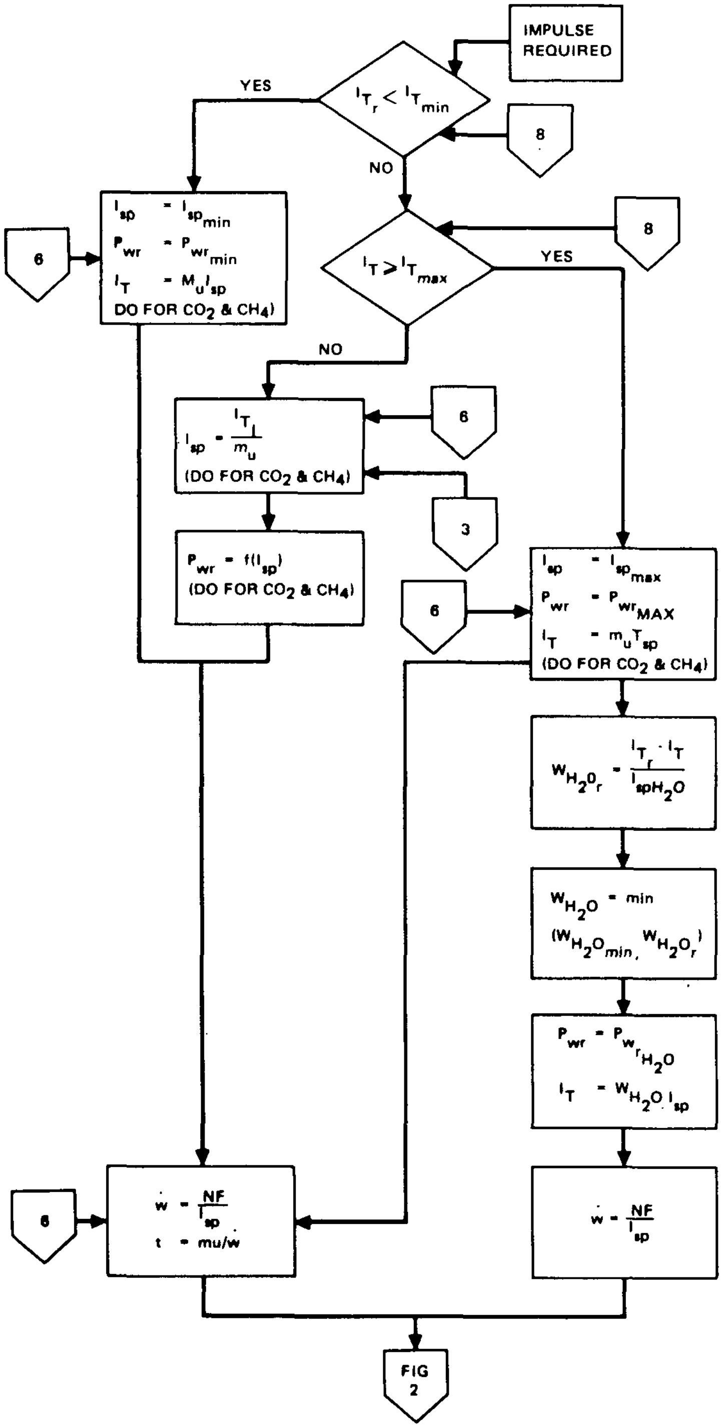
T_o = Orbit period

ΔP_Ω = Drag impulse for resistojets

N_2 = Number of thrustors for orbit-keeping.

FLOW LOGIC

DESCRIPTION



TEST TO SEE IF POWER IS REQUIRED

IF NOT, COMPUTE MINIMUM SPECIFIC IMPULSE AND TOTAL IMPULSE

TEST IF MAXIMUM POWER IS REQUIRED

IF NOT, USE IMPULSE SPLIT FROM FIGURE A-8 TO CALCULATE CO_2 AND CH_4 SPECIFIC IMPULSE

DETERMINE POWER REQUIRED FOR EACH PROPELLANT. POWER WILL BE A FUNCTION OF THRUSTOR DESIGN.

IF IMPULSE REQUIRED EQUALS OR EXCEEDS THAT AVAILABLE, USE MAXIMUM SPECIFIC IMPULSE AND CALCULATE POWER AND TOTAL IMPULSE FOR BOTH CO_2 AND CH_4

WATER SUPPLEMENT EQUALS DIFFERENCE IN IMPULSE DIVIDED BY MAXIMUM WATER SPECIFIC IMPULSE.

ACTUAL WATER USED IS MINIMUM OF WATER REQUIRED AND WATER ALLOWED TO BE USED IN ANY ONE FIRING TIME. IF WATER AVAILABLE IS NOT SUFFICIENT, HIGH THRUST MUST BE USED.

CALCULATE WATER POWER LEVEL AND TOTAL IMPULSE.

CALCULATE FLOW PATHS AND USAGE TIMES FOR ALL PROPELLANTS

Figure A-12. System Performance Characteristics

dependent on the Space orientation and the relative size of the orbit keeping impulse to the desaturation impulse. The thrustor firing durations are set in the respective thrustor firing time accumulators and at the computed firing times the resistojets and high thrustors (if required) are activated. The orbit timer is used to activate and deactivate the thrustors. A test is then performed to determine if the correct number of thrustor firings have been made. At the completion of the orbit the desaturation impulse update is computed from the CMG gimbal angles and the orbit keeping impulse update is computed from the integrated output of the accelerometer.

From Table A-2 for the case of the horizontal orientation, two firing angles per orbit are used to provide the combined functions of orbit keeping and CMG desaturation.

Assuming two firing angles per orbit the yaw and pitch desaturation firing angles are expressed by Equations 9 and 10 in Table A-2. These are for the normal case with the orbit-keeping impulse greater than the desaturation impulse.

At the completion of the orbit, the start of the first firing angle for the yaw desaturation operation in degrees is $(180 + \phi_o - \Psi_{fs}/2)$ and the start of the second firing angle is $(360 + \phi_o - \Psi_{fs}/2)$. The parameter ϕ_o is given by Equation (3) in Table A-1.

Assuming the desaturation operation produces an orbit-keeping impulse the firing angle for the drag impulse is given by Equation 11.

The starting position of the orbit-keeping firing angle is computed as $(180 + \phi_o - \phi_{fd}/2)$ and the second firing angle is $(360 + \phi_o - \phi_{fd}/2)$ where $\phi_{fd} = \phi^{1}_{fd} + \Psi_{fs} + \theta_{fs}$. The firing angles for combining the orbit keeping and desaturation impulse are shown in Figure A-13, which reveals the bio-waste thrustor firing angles required for a Space Station in a horizontal orientation. In this orientation, the orbit-keeping and desaturation impulse functions are combined. It is noted that the orbit-keeping impulse is much greater than the desaturation impulse.

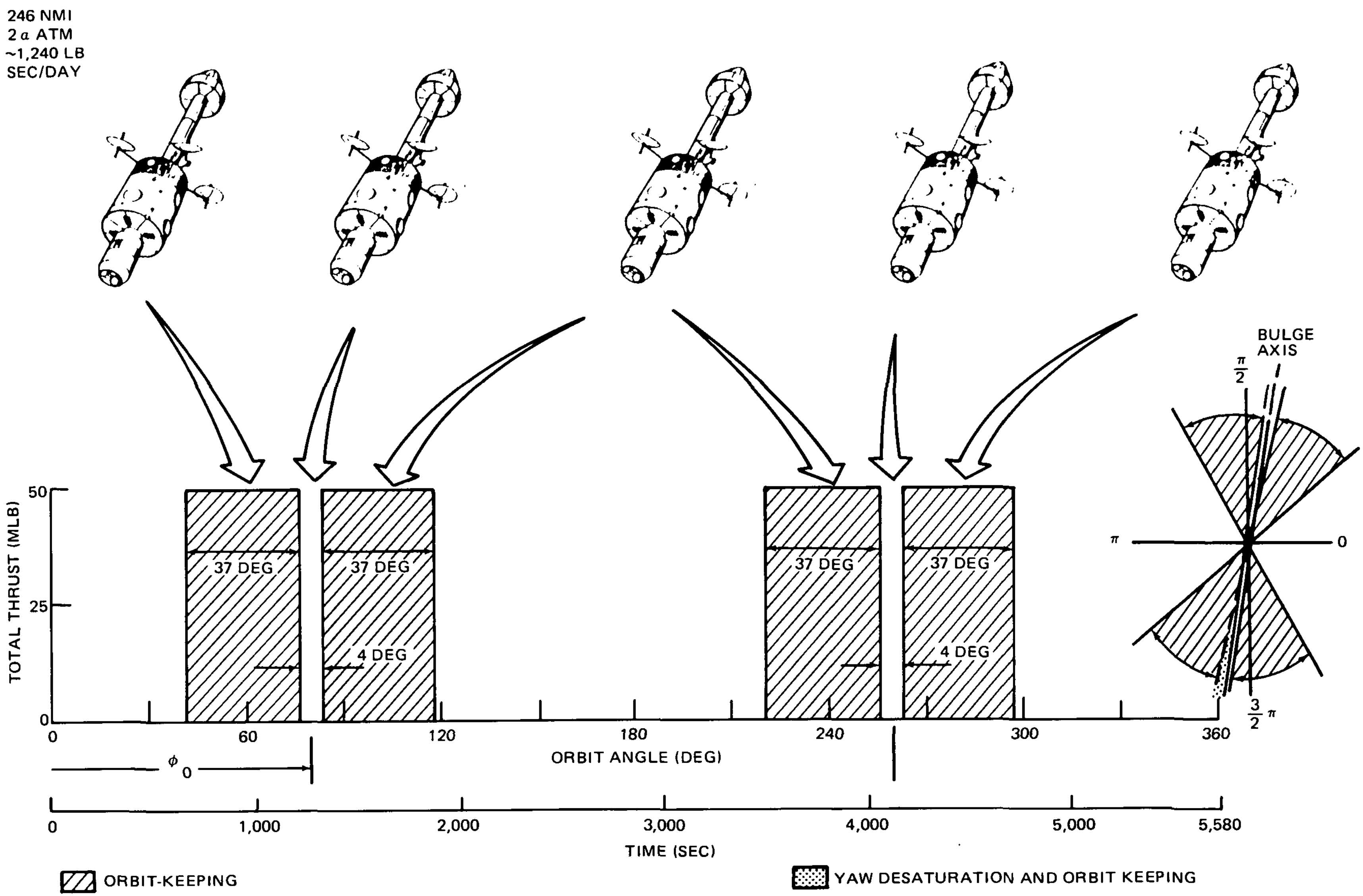


Figure A-13. Typical Orbit Operation Thrust Schedule (Horizontal Orientation)

If the desaturation and orbit-keeping functions are not combined, then the second term in the brackets of Equation (11) in Table A-2 is omitted.

If the desaturation impulse is larger than the orbit-keeping impulse, then the order of computing the firing angles must be reversed as given by Equations (9) and (10). Assuming the orbit keeping and desaturation functions are combined, the firing angles for this reversed case are computed in a similar manner.

The excess impuse (if any) allocated to the high-thrust system will be expended into two firing angles, the same as the resistojets. However, due to the relatively short firing time for the high-thrust system the thrustor firing will be at the two firing angles of $(180 + \phi_0)$ and $(360 + \phi_0)$ deg. This position is illustrated in Figure A-13.

The thrustor firing angles for the X-POP/OR orientation will be computed in the same manner as those for the horizontal orientation. The only difference would be for the case of combining the case of combining the orbit-keeping and desaturation functions. For the X-POP/OR orientation the firing angles are computed for the roll and yaw axes instead of the pitch and yaw axes for the horizontal orientation. The roll and yaw firing angles are given in Table A-2 as Equations 12 and 13, respectively, and the orbit-keeping firing angle is given by Equation 14.

The firing angles for the orbit-keeping mode in the X-POP orientation will be divided into four equal angles spaced at equal intervals. With this operation, equal firing times of the four thrustor quadrants are obtained.

The firing angles for the roll, pitch and yaw desaturation impulse requirements are also based on four firing angles for each orbit and are given by Equations 15, 16, and 17 of Table A-2.

In combining the orbit-keeping and the desaturation functions, the firing angle for the orbit-keeping is given by Equation 18 of Table A-2.

Figure A-14 shows the firing angles for the combined orbit-keeping and desaturation operation in the X-POP orientation. One set of engines in one of

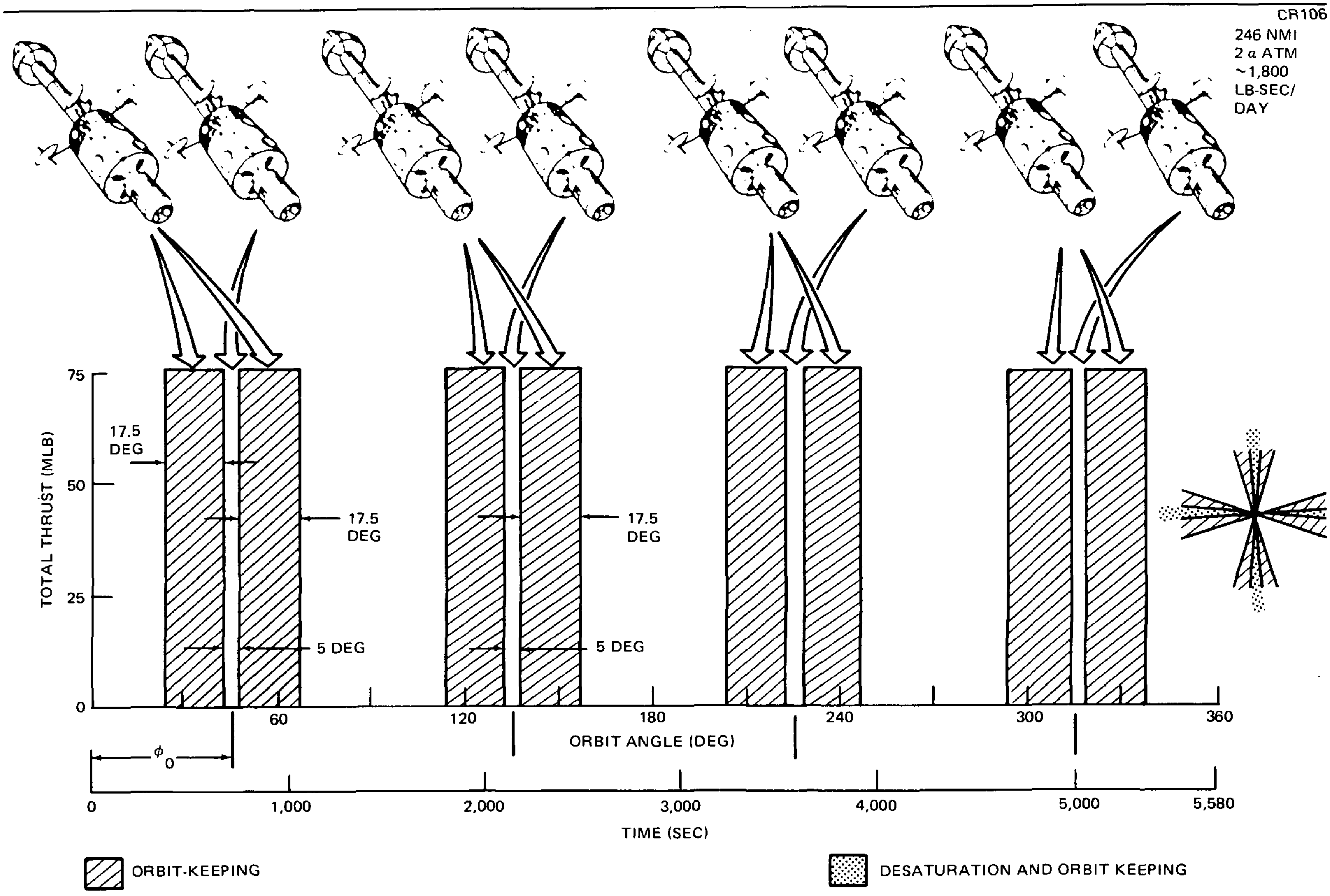


Figure A-14. Typical Orbit Operation Thrust Schedule (Pop Orientation)

the four quadrants is used for one firing angle. After the first orbit, the starting position of the first firing angle is $(90 - \psi_{fd}/2)$, the second firing angle starts at $(180 - \psi_{fd}/2)$, the third at $(270 - \psi_{fd}/2$ and the fourth at $(360 - \psi_{fd}/2)$. The pitch (yaw) thrustors are fired at the first and third angles while the yaw (pitch) thrustors fire in second and fourth firing angles.

A.4 IMPULSE AVAILABLE

The impulse estimates are a function of total impulse required. If the total impulse is greater than that available, the CO_2 and CH_2 will be operated at maximum temperature. Similarly, if the required impulse is less than the minimum available, both gases will be used at minimum temperature (no power unless other constraints, such as contamination, require heating). If the impulse required is between these extremes, identical chamber temperatures will be used if possible (CH_4 limit is 1,800°R, but CO_2 can be used to 2,880°R).

$$I_{T_{CH_4\,max}} = m_{g_{CH_4}} \; I_{sp_{CH_4 max}}$$

$$I_{T_{CH_4 min}} = m_{g_{CH_4}} \; I_{sp_{CH_4 min}}$$

$$I_{T_{CO_2 max}} = m_{g_{CO_2}} \; I_{sp_{CO_2 max}}$$

$$I_{T_{CO_2 min}} = m_{g_{CO_2}} \; I_{sp_{CO_2 min}}$$

$$I_{T_{CO_2}}\underset{1000\,°R}{} = m_{g_{CO_2}} \; I_{so_{CO_2}}\underset{1000\,°R}{}$$

If $I_{T_{req}} > \Sigma I_{T_{max}}$, then

$$I_{T_{CH_4}} = I_{T_{CH_4 max}}, \text{ and}$$

$$I_{T_{CO_2}} = I_{T_{CO_2 max}}$$

If $I_{T_{req}} < \Sigma I_{T_{min}}$, then

$$I_{T_{CH_4}} = I_{T_{CH_4 min}}, \text{ and}$$

$$I_{T_{CO_2}} = I_{T_{CO_2 min}}$$

If $I_{T_{req}} \quad T_{T_{CH_4 max}} + I_{T_{CO_2}}$, then

1,000 °R

$r = 1.65$

if not, $r = 1.65 - 0.45 \dfrac{I_T - I_{T_{1,000\,°R}}}{I_{T_{max}} - I_{T_{1,000\,°R}}}$, and

$$I_{T_{CH_4}} = I_{T_{req}} \frac{r}{r + \dfrac{m_{g_{CO_2}}}{m_{g_{CH_4}}}}$$

$$I_{T_{CO_2}} = I_{T_r} \frac{1}{1 + r \dfrac{m_{g_{CH_4}}}{m_{g_{CO_2}}}}$$

A. 5 NOMENCLATURE FOR APPENDIX

T_o	Orbit Period
h	Angular Momentum
m	Propellant Mass
P	Storage Pressure
P_T	Test Pressure
P_B	Preset Blowdown Pressure
P_D	Preset Storage Pressure
V	Storage Volume
R	Gas Constant
T	Storage Temperature
I_T	Total Impulse
I_{SP}	Specific Impulse
ΔS	Impulse
F	Thrust
t	Time
W_P	High-Thrust System Propellant Mass
ϕ	Roll Axis Firing Angle
ψ	Yaw Axis Firing Angle
θ	Pitch Axis Firing Angle
r	Ratio of I_{TCH4} to I_{TCO_2}
ΔV	Velocity

<u>Subscripts</u>

CH_4	Methane
CO_2	Carbon Dioxide
H_2O	Water

x, y, z	Principal Axes
MIN	Minimum
MAX	Maximum
sr	Storage Required
u	Usable
i	CH_4 or CO_2
sa	Storage Available
sc	Storage Maximum (Preset)
g	Generated
MEAS	Measured (Data)
COMP	Computed
AVAIL	Available
P, Y, R	Pitch, Yaw, Control
fs	Desaturation Firing Angle
fd	Orbit Keeping Plus Desaturation Firing Angle
br	Blowdown Required
ba	Blowdown Available
bc	Blowdown Maximum (Preset)
s	Storage
b	Blowdown